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Evaluation of the Structural Performance of CTS Rapid Set Concrete Mix®

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Geotechnical and Structures Laboratory

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Final report

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Abstract

During the period October 2013 through June 2015, research was conducted at the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, MS, to develop pavement design curves for airfield damage repairs (ADR) using Rapid Set Concrete Mix®. This report presents the technical evaluation of the field performance of full-depth concrete repairs conducted using Rapid Set Concrete Mix® over varying strength foundations and also presents the results of laboratory data collected during field testing. Passes-to-failure rates for each repair were determined using an F-15E load cart and were compared to those predicted using the Department of Defense's (DoD) rigid pavement design method. Results indicate that the DoD's rigid pavement design criteria are conservative at low pass levels with rapid-setting concrete and that the design guidance presented in this report should be used for ADR repair performance prediction purposes.

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Preface

This study was conducted for the U.S. Air Force Civil Engineer Center (AFCEC) under the project "Structural Performance of Rapid Set Concrete Mix®." The Technical Monitor was Dr. Craig Rutland, AFCEC.

The work was performed by the Airfields and Pavements Branch (GMA) of the Engineering Systems and Materials Division (GM), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Timothy W. Rushing was Chief, CEERD-GMA; Dr. Gordon W. McMahon was Chief, CEERD-GM; and Nicholas Boone, CEERD-GVT, was the Technical Director for Force Projection and Maneuver Support. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Bartley P. Durst.

COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
Inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
tons (force)	8,896.443	newtons

1 Introduction

1.1 Problem

Since 2006, researchers at the U.S. Army Engineer Research and Development Center (ERDC) have been conducting research under the Airfield Damage Repair (ADR) Modernization Program to develop expedient concrete pavement repair techniques in an effort to update repair guidance for military airfields. Damaged pavements must be repaired using fast methods and durable materials to reduce the total time that the pavement is removed from service, as well as to reduce the need to conduct subsequent repairs to maintain an operable pavement surface, particularly during wartime scenarios. The objective of the ADR Modernization Program is to develop capabilities to rapidly repair damaged airfield pavements for the full spectrum of operational scenarios including base recovery after an attack, expedient repairs at deployed locations, and sustainment of operating surfaces at forward operating bases. In addition to military wartime repair scenarios, damaged military and civilian airfields must also be repaired quickly; and these repairs must be capable of withstanding aircraft traffic at full operational levels to ensure long-lasting repairs.

Cementitious, rapid-setting concrete repair materials have been successfully used as a capping material for repairing bomb-damaged concrete pavements under the ADR Modernization Program. Since 2006, more than 150 repairs have been conducted using proprietary, rapid-setting concrete repair materials. Timing data collected during numerous field trials during this time indicated that use of several different commercial products can produce a repair that will return an airfield to traffic within the objective total repair time frame of 6.5 hr and can withstand aircraft traffic following a short curing time of 2 hr. Based on results from numerous projects during this time, Rapid Set Concrete Mix® was identified as a versatile repair material and was recommended for a variety of repair types including spall repair, small and large patches, full-slab replacement, and small and large crater repairs (Priddy 2011). Successful field results under simulated and actual aircraft maneuvers (C-17 and F-15E) (Priddy et al. 2011), ease-of-placement, and versatility with concrete mixing equipment led to the recommendation of this repair material for all ADR operational scenarios with potential application to peacetime repair activities.

These peacetime repair activities include any repairs not associated with bomb damage such as spall repairs, partial slab replacements, and full slab replacements caused by overloading of the pavement by aircraft or loss of foundation support. Additional applications for these materials include emergency pavement repairs after natural disasters.

While numerous repairs have been conducted with rapid-setting concretes, specific guidance is lacking on the number of aircraft passes Rapid Set Concrete Mix® can sustain when used as a repair material. As a result, in 2013, the U.S. Air Force (USAF) initiated the effort described in this report.

1.2 Objective and scope

The objective of the research presented in this report was to develop pavement design curves relating CTS Rapid Set Concrete Mix® repair material cap thickness, backfill material thickness, and backfill material strength to passes of an F-15E aircraft. Design curves were needed to predict the life of a repair when capped with Rapid Set Concrete Mix® and to determine the impact of backfill material quality and thickness on service life. To achieve the objective, a number of pavement repairs were conducted by varying rapid-setting concrete cap thicknesses over different foundation compositions and strengths to determine the passes-to-failure for the rapid-setting material capped repairs under F-15E traffic. Additionally, current rigid pavement design criteria and performance prediction software were reviewed to determine whether current criteria could be used for analyzing rapid-setting concrete capped repairs. Following completion of these steps, design guidance for rapid-setting concrete was developed.

This report describes the full-scale field testing in Chapter 2. Chapter 3 presents repair procedures, and Chapter 4 presents the repair performance results. Chapter 5 shares analyses and discusses results, while Chapter 6 notes pertinent conclusions and recommendations.

2 Full-Scale Field Testing

Twenty-one repairs were completed in support of this research effort. The study was conducted in five series of repair efforts, as shown in Table 1. All repair sizes were approximately 8.5 ft by 8.5 ft. The following sections describe the test sections utilized to conduct repairs, the repair material, the repair test matrix, the trafficking procedures, the failure criteria, and the data collection procedures.

Table 1. Repair matrix.

Series	Repair Number	Rapid Set Concrete Mix® Cap Thickness (in.)	Base Material	Base Thickness (in.)	Subgrade
1	1	6	None	0	silty clay
	2	8	None	0	silty clay
	3	10	None	0	silty clay
	4-1[a]	12	None	0	silty clay
	4-2	12	None	0	silty clay
	5-1[a]	14	None	0	silty clay
	5-2	14	None	0	silty clay
2	6	6	GW	6	silty clay
	7-1[b]	8	GW	6	silty clay
	7-2	8	GW	6	silty clay
	8	10	GW	6	silty clay
3	9	6	flow fill	6	silty clay
	10-1[c]	8	flow fill	6	silty clay
	10-2	8	flow fill	6	silty clay
	11	10	flow fill	6	silty clay
4	12	6	flow fill	12	silty clay
	13	8	flow fill	12	silty clay
	14	10	flow fill	12	silty clay
5	15	6	GW	12	silty clay
	16	8	GW	12	silty clay
	17	10	GW	12	silty clay

[a] Repair repeated due to wet subgrade conditions noted after failure

[b] Repair repeated due to early failure of the repair

[c] Repair repeated due to shattered slab occurring after 560 passes

2.1 Test sections

Four existing full-scale test sections were utilized to conduct the repair activities to alleviate the expense of constructing new pavements or traveling to other testing locations. These test sections included

- FY13 Saw-Cutting Technologies Test Section,
- FY12 Precast Slab Test Section,
- FY12 Marginal Materials Test Section, and
- FY14 ADR Concrete Cutting Refinement Test Section.

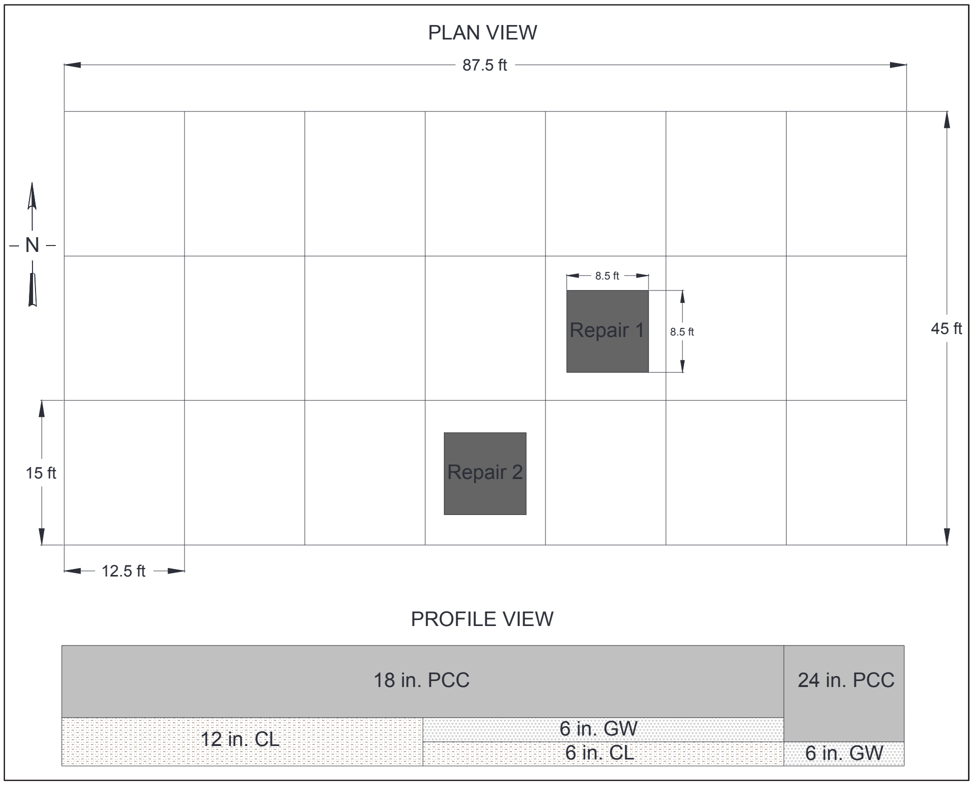
The following sections summarize the as-built pavement structures and material properties for the test sections. Additional details of their construction are available in Edwards et al. (2015), Bly et al. (2013), Bly (2012), and Bell et al. (2015), respectively.

2.1.1 FY13 Saw-Cutting Technologies Test Section

The FY13 Saw-Cutting Technology Test Section was constructed at the ERDC's Poor House Property test site in Vicksburg, MS, in 2013 to investigate various combinations of cutting and excavation equipment for small crater repairs. It consisted of 18- and 24-in.-thick portland cement concrete (PCC) placed over varying base course materials, as shown in Figure 1. Repairs 1 and 2 of Series 1 were conducted in this test section. The western half of the pavement structure consisted of 18 in. of PCC over 12 in. of low-plasticity clay with sand classified as CL by the Unified Soil Classification System (USCS) described in ASTM D 2487 (2011). The eastern half of the pavement structure consisted of 18- and 24-in.-thick PCC over 6 in. of crushed limestone material classified as gravel (GW). A 6-in.-thick layer of silt was added under the limestone base course of the 18-in.-thick PCC to achieve elevation.

The pavement structure was originally designed to evaluate the saw-cutting capabilities of various equipment in thick PCC and was not designed for a specific aircraft traffic pass level. However, the pavement was capable of supporting at least 50,000 passes of C-17 aircraft traffic when the pavement structure was analyzed using PSeven pavement design software.

Figure 1. Plan view, profile view, and location of repairs in FY13 Saw-Cutting Technologies Test Section.

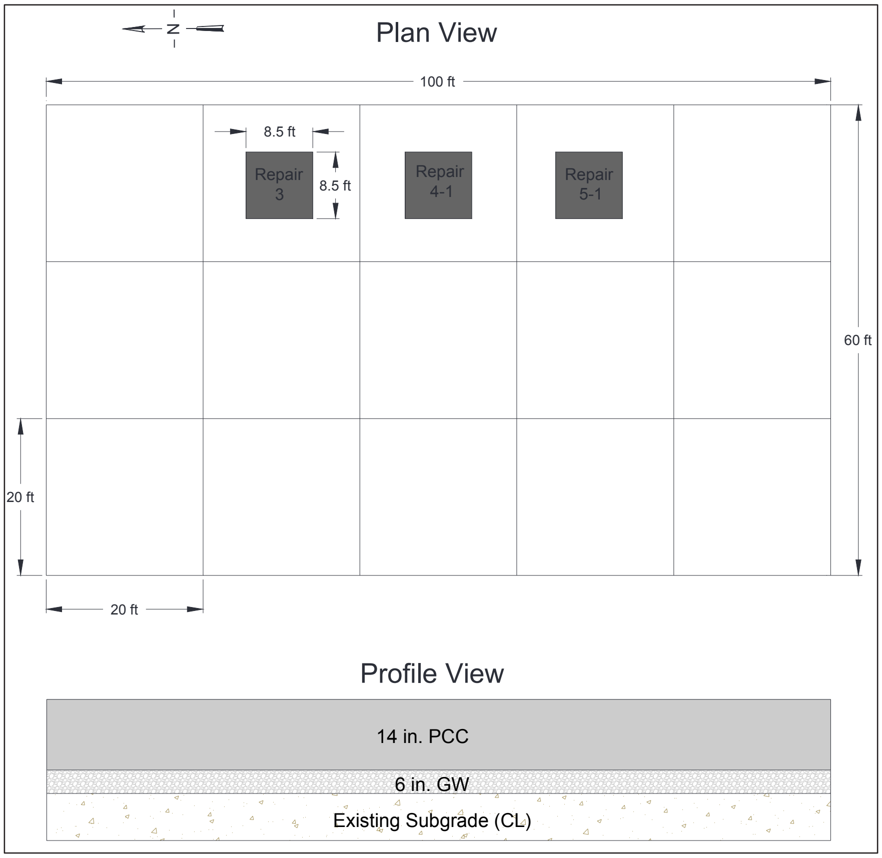


The concrete mixture was a locally available, fixed-form PCC with average 28-day unconfined compressive strength (UCS) and flexural strength test results (completed in accordance with ASTM standards C39 [2010] and C78 [2010]) of 6,500 and 600 psi, respectively. Each slab size was 12.5 ft by 15 ft. The slab dimensions were in accordance with DoD specifications, UFC 3-260-02, for PCC airfield pavements (UFC 2001).

2.1.2 FY12 Precast Panel Test Section

The FY12 Precast Panel Test Section was also constructed at the Poor House Property at the ERDC from April through July 2011. It consisted of 15 20-ft by 20-ft by 14-in. slabs as shown in Figure 2. Repairs 3, 4-1, and 5-1 of Series 1 were completed in this test section. The pavement structure was designed to evaluate the performance of precast concrete panel repairs under simulated C-17 aircraft traffic. Both PCASE and PSeven software were used to determine the optimum pavement structural design using locally available materials that would withstand 50,000 passes of a C-17 aircraft. The resulting pavement structure consisted of 14 in. of PCC over 6 in. of base course, with a California bearing ratio (CBR) of 37, over a subgrade with CBR of 14.

Figure 2. Plan view, profile view, and location of repairs in FY12 Precast Panel Test Section.



The subgrade consisted of low-plasticity clay with sand (CL). The base course was a limestone material classified as gravel (GW). The effective modulus of subgrade reaction, k, determined from plate load testing conducted on the surface of the base was 276 lb/in.^{3}.

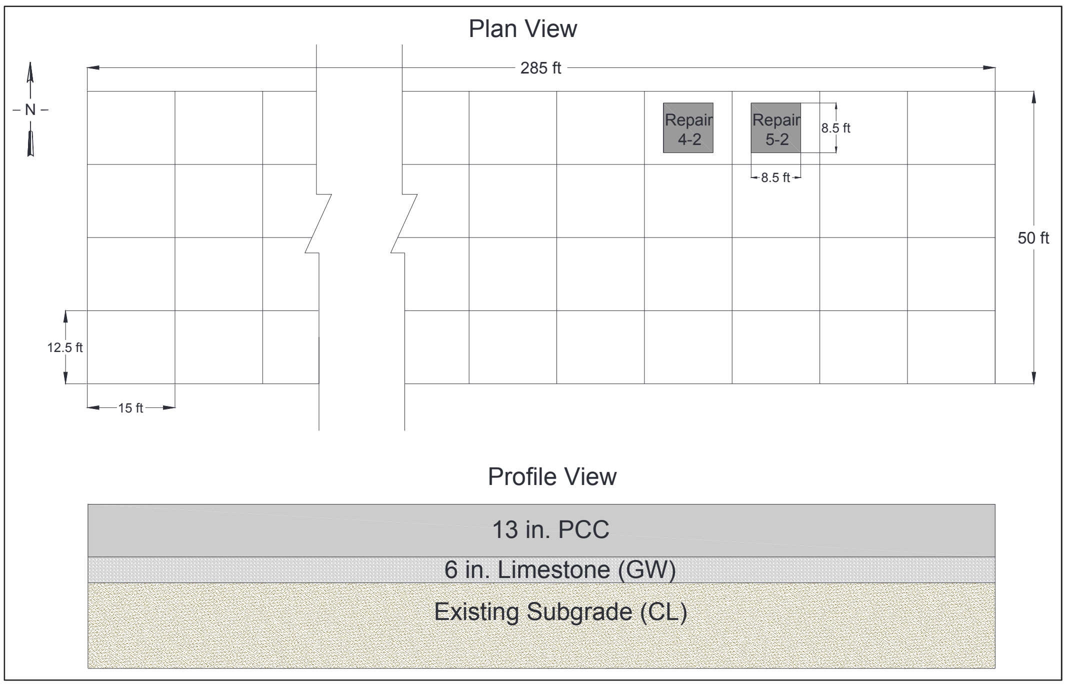
The concrete was a locally available, 650-flexural strength (5,000 psi UCS) fixed-form PCC. The average 28-day UCS and flexural strength results were 7,240 and 940 psi, respectively. These average 28-day results are well above the minimum requirements for airfield pavements, 5,000 and 650 psi, respectively.

2.1.3 FY12 Marginal Materials Test Section

The FY12 Marginal Materials Test Section was constructed at the Poor House Property at the ERDC in November 2011. It consisted of 76 15-ft by 12.5-ft by 13-in. slabs, as shown in Figure 3. Two repairs not constructed with marginal materials were completed in the portion of this test section. The pavement structure was designed to evaluate the performance of

marginal-quality concrete mixtures under simulated F-15E aircraft traffic. PCASE software was used to determine the optimum pavement structural design using locally available materials that would withstand 50,000 passes of an F-15E aircraft. The resulting pavement structure consisted of 13 in. of PCC over 6 in. of a gravel (GW) base course over 12 in. of a compacted silty clay subgrade with a soil classification of low-plasticity clay (CL). The effective modulus of subgrade reaction, k, determined from plate load testing conducted on the surface of the base was 206 psi/in.

Figure 3. Plan view, profile view, and location of repairs in Marginal Materials Test Section.



The concrete was a locally available, 650-flexural strength (5,000 psi UCS) fixed-form PCC. The average 28-day UCS and flexural strength results were 8,010 and 820 psi, respectively. These average 28-day results are well above the minimum requirements for airfield pavements (5,000 and 650 psi, respectively).

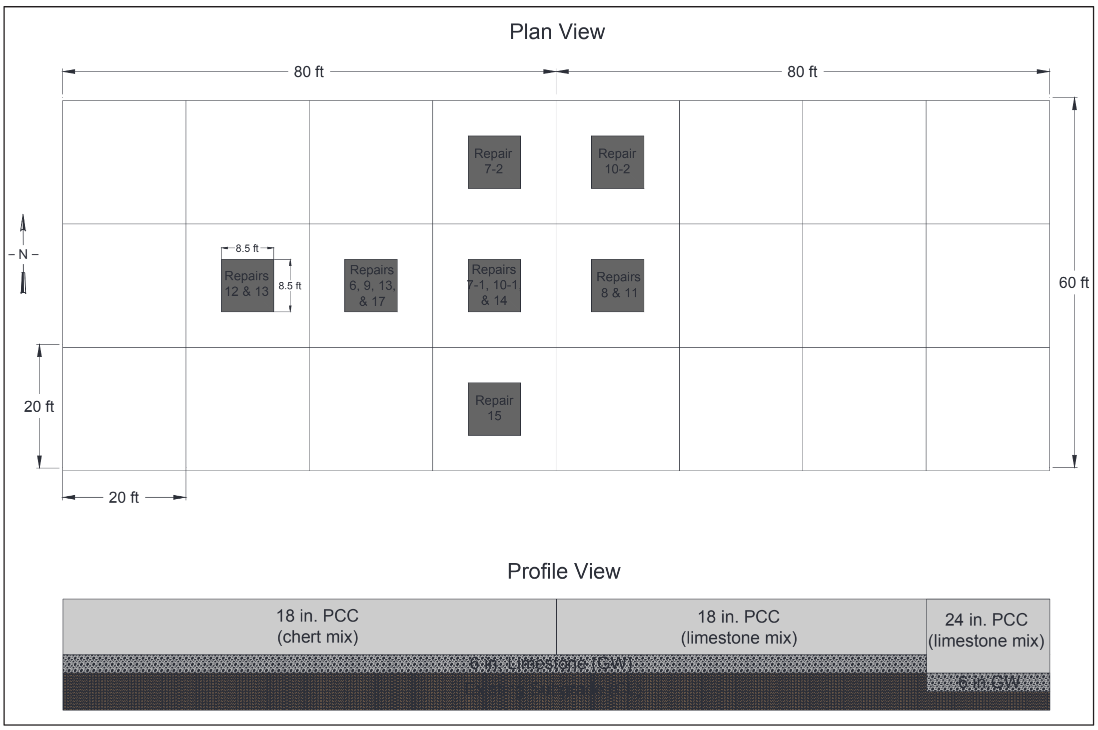
2.1.4 FY14 Concrete Cutting Refinement Test Section

The FY14 Concrete Cutting Refinement Test Section, with dimensions of 60 ft wide and 160 ft long and with 24 20-ft by 20-ft slabs, was constructed on ERDC's Poorhouse property in the same location as the FY13 Saw-Cutting Technologies Test Section. The pavement structure was originally designed to evaluate the saw-cutting capabilities of various equipment in thick PCC and was not designed for a specific aircraft traffic pass level.

However, the pavement was capable of supporting at least 50,000 passes of C-17 traffic when the pavement structure was analyzed using PSeven.

Fourteen repairs were completed in this test section. Twelve of the PCC slabs were 18 in. thick and constructed with a chert aggregate mix, nine of the slabs were 18 in. thick and constructed with a limestone aggregate mix, and three of the slabs were 24 in. thick and constructed with a limestone aggregate mix. A 6-in.-thick limestone aggregate base (GW) was compacted on top of the existing low-plasticity clay (CL) subgrade. Figure 4 shows the plan and profile views of the test section and the location of the repairs.

Figure 4. Plan view, profile view, and location of repairs in FY14 Concrete Cutting Refinement Technologies Test Section.



All materials and concrete (the PCC, limestone aggregate base course, and subgrade materials) were characterized in the laboratory by ERDC's Materials Testing Center and through in situ measurements by APB technicians. The average 28-day UCS and flexural strength results for the chert PCC mix were 6,340 and 860 psi, respectively. The average 28-day compressive and flexural strength results for the limestone PCC mix were 6,070 and 785 psi, respectively. These results are well above the minimum requirements for airfield pavements (5,000 and 650 psi, respectively).

2.2 Repair materials

When pavement repairs are conducted, the required repair depth depends on the extent of disturbed material. General airfield design and repair guidance (UFC 2001) recommends a minimum repair PCC cap thickness of 6 in. regardless of aircraft type. Other than very shallow repairs requiring only the placement of a repair cap, the majority of repairs require the placement of backfill material to provide a base/platform on which to place the cap and to minimize the amount of rapid-setting concrete (or other PCC material) required to complete the repair. The repair materials included in this investigation were Rapid Set Concrete Mix® as the capping material and crushed limestone (GW) or rapid-setting flowable fill as backfill materials. Each material is described in the following subsections.

2.2.1 CTS Rapid Set Concrete Mix®

The rapid-setting concrete used for the study was CTS Rapid Set Concrete Mix®. The main cementitious component in the mix is Rapid Set Cement, a proprietary, calcium sulfoaluminate-based material that accelerates the hardening time. The aggregate used in the mix is 3/8-in. maximum size pea gravel. The material is factory blended and stored in large 3,000-lb super sacks fashioned from woven geotextile fabric and lined with plastic.

Because the material is pre-blended, the only component required during the mixing process is water, and the material can be mixed using a variety of equipment. Equipment suitable for mixing the material includes buckets with paddle mixers, mortar mixers, commercial volumetric mixers, and rotating drum transit trucks. Following development and validation in previous ADR Modernization Program projects, a simplified volumetric mixer was identified as the fastest and most consistent method of mixing and placing rapid-setting concrete (Priddy et al. 2013).

Per manufacturer's recommendation, bulk citric acid can be added to the mix water to increase the working time of the material and to prevent flash setting of material within the mixer at air temperatures greater than 85°F. Aluminum sulfate can be added in bulk to accelerate the set time of the mix for placement of repairs at air temperatures less than 40°F (Edwards et al. 2013). The material is placed in a manner similar to ordinary concrete, but it must be placed expediently since it begins to harden and set within 15 to 30 min.

Unlike ordinary PCC, this material can sustain heavy aircraft traffic within 2 hr after placement. Laboratory results collected during several periods of field and material certification testing have shown that this material achieves UCS (ASTM C39 2010) in excess of 3,000 psi after 2 hr and over 5,000 psi after 28 days. In addition to UCS, flexural strengths (ASTM C78 2010) obtained using this material are in excess of 350 psi after 2 hr and 650 psi after 28 days. Laboratory results are presented in Priddy (2011) and are not included in this report for brevity.

A series of laboratory tests was conducted to characterize the material in terms of its UCS, flexural strength, modulus of elasticity, and time of set in accordance with ASTM procedures C39 (2010), C78 (2010), C469 (2014), and C403 (2008), respectively, using two water/cement (w/c) ratios: 0.35 (manufacturer recommended w/c ratio) and 0.42 (representative of field placement) at early ages. The difference in recommended and field placement w/c ratio is attributed to the use of additional water to prevent flash-setting of large volumes of material and to provide increased workability. Previous field tests have shown that placing the material at the 0.35 w/c ratio for large placements is difficult.

Measurements were conducted during early curing durations from 0.5 to 48 hr, as shown in Table 2, to determine whether the increase in water was detrimental to repair performance in terms of measured properties at early test ages. Because the 28-day UCS data were not measured during these tests, the average UCS at 28 days reported in the table is from previous experiments (Priddy et al. 2013) and is provided for comparison. In addition, vendor-reported material properties are included in Table 2 for UCS and flexural strength. The vendor does not report values for elastic modulus.

Table 2 shows that some variation in strength measurements occurred. These variations are attributed to the manner in which the samples were cast expediently in the laboratory to allow tests to be conducted after very short curing durations. The data show that the increase in water does not appear to significantly affect the strength gain for the material for the purposes of rapid crater repair. The data also show that the material gains the majority of its ultimate strength in very short curing durations. After 1 hr of cure, at a w/c ratio recommended by the manufacturer, 55 percent of the 28-day UCS may be achieved, and after 24 hr, 100 percent of the vendor-reported UCS (5,000 psi) may be achieved. After 2 hr, 77 percent

of the vendor-reported 28-day flexural strength could be achieved. These results differ from traditional Type I or II cement mixtures that gain strength slowly; they generally obtain 60 percent of their 28-day UCS occurs after three days.

Table 2. Laboratory results for CTS Rapid Set Concrete Mix®.

Cure Time (hr)	Measured Properties w/c = 0.35			Measured Properties w/c = 0.42			Predicted Properties[a] w/c = 0.35	
	UCS (psi)	Flexural Strength (psi)	Elastic Modulus (psi)	UCS (psi)	Flexural Strength (psi)	Elastic Modulus (psi)	UCS (psi)	Flexural Strength (psi)
1.0	4,380	----[c]	-----[c]	-----[c]	-----[c]	-----[c]	3,000	-----[a]
1.5	4,090	-----[c]	-----[c]	1,730	-----[c]	-----[c]	-----[a]	-----[a]
2.0	4,710	580	2,995,110	4,840	445	3,270,440	-----[a]	420
3.0	5,720	720	3,481,405	5,280	585	3,337,380	-----[a]	-----[a]
4.0	4,680	590	3,552,550	5,110	610	3,838,745	4,000	-----[a]
8.0	6,060	520	3,634,520	6,120	590	3,940,820	-----[a]	-----[a]
24.0	7,340	590	4,247,060	5,690	630	3,980,560	5,000	650
48.0	6,710	590	4,264,810	6,760	600	4,208,055	-----[a]	-----[a]
28.0 days[b]	7,870	-----[b]	----[b]	-----[b]	-----[b]	-----[b]	6,000	750

[a] Vendor data sheet http://www.ctscement.com/Specs2005/PDFdocs/Data_Sheets/ConcreteMix_data.pdf; missing data not supplied

[b] 28-day data from Priddy et al. (2013); other tests not conducted

[c] Sample not sufficiently cured to obtain measurement during testing.

2.2.2 Rapid-setting flowable fill

The flowable fill used for this study was Buzzi Unicem Utility Fill 1-Step 750. This is a rapid-setting flowable fill material that consists of a dry blend of rapid-setting cement and fine aggregates stored in large 3,000-lb super sacks fashioned from woven geotextile fabric and lined with plastic. As with the rapid-setting concrete, the pre-blended material requires only the addition of water to conduct repair activities.

This material was selected for ADR operations because it can be placed expediently without the need of mixing equipment by using the placement technique known as the “dry method” (Priddy et al. 2013). In this method, thin 4- to 6-in.-thick lifts of dry material are placed, and then approximately 40 gal of water is applied to the surface of each lift and allowed to percolate through the dry material. When used with a rapid-setting concrete cap, the flowable fill provides sufficient bearing capacity for heavy aircraft pavement applications, as demonstrated in numerous field experiments (Bell et al.

2013, Edwards et al. 2013, Priddy et al. 2013, Carruth et al. 2015) and generally provides a UCS of 250 psi after 30 min of cure time and 750 psi after 3 hr of cure time. Post-trafficking investigations typically reveal a CBR of approximately 100 percent after 24 hr of cure time.

2.2.3 Crushed limestone

A #610 crushed limestone (GW) base material was procured from a local source in Vicksburg. This material was selected for its high compacted strength and availability and from previous use as a repair backfill material. Previous laboratory tests conducted on this material have shown that it meets the requirements detailed in UFGS 32.11.16.16: *Base Course for Rigid Paving* (Bly 2012). The material was placed and compacted in 3- to 4-in.-thick lifts to prepare a base on which the rapid-setting cap could be placed.

2.2.4 Silt

Silt was used as the subgrade material for each of the repairs. The 4- to 6-CBR material was placed and compacted in three approximately 6-in.-thick lifts to prepare a consistent subgrade on which the various backfill materials could be placed.

2.3 Repair test matrix

As mentioned previously, five series of repairs were conducted to determine the effect that varying cap thickness, base thickness, and base type has on the passes-to-failure for rapid-setting concrete (Table 1). The excavated repair dimensions and date of cap completion are presented in Table 3. The following subsections describe each series of repairs.

2.3.1 Series 1 repairs

Series 1 replicated situations in which backfill material was either unavailable to complete the repairs or local subgrade materials were used as backfill. The rapid-setting cap thickness was increased in 2-in.-thick increments from a minimum thickness of 6 in. to a maximum of 14 in., while holding the subgrade type (silty clay) and strength (target 4 to 6 CBR) constant. The 6-in.-thickness is currently the minimum airfield thickness for designing PCC pavements or conducting PCC repairs. The performance of these Series 1 repairs was used to develop a design curve relating rapid-setting cap thickness to passes-to-failure when the repair cap is placed on a moderately weak foundation.

Table 3. Repair locations, sizes, and start dates.

Series No.	Repair No.	Test Section	Repair Dimensions (in. x in. x in.)	Repair Date
1	1	FY13 Saw-Cutting Technologies	103 x 103 x 32.5	5 Nov. 2013
	2	FY13 Saw-Cutting Technologies	101 x 103.5 x 34	6 Nov. 2013
	3	FY12 Precast Panel	102.5 x 103 x 32.5	15 Nov. 2013
	4-1[a]	FY12 Precast Panel	104.5 x 103.5 x 33	20 Nov. 2013
	4-2	FY12 Marginal Materials	103 x 103 x 32	27 Mar. 2014
	5-1[a]	FY12 Precast Panel	104 x 102.5 x 33	20 Nov. 2013
	5-2	FY12 Marginal Materials	103 x 104 x 34	27 Mar. 2014
2	6	FY14 Concrete Cutting Refinement	102 x 103 x 33	7 Jul. 2014
	7-1[a]	FY14 Concrete Cutting Refinement	103 x 103 x 35	7 Jul. 2014
	7-2	FY14 Concrete Cutting Refinement	101.5 x 110.5 x 34	18 Dec 2014
	8	FY14 Concrete Cutting Refinement	102 x 105 x 34	7 Jul. 2014
3	9	FY14 Concrete Cutting Refinement	102.5 x 108.5 x 34	22 Aug. 2014
	10-1[a]	FY14 Concrete Cutting Refinement	104.5 x 111.5 x 34	22 Aug. 2014
	10-2	FY14 Concrete Cutting Refinement	103 x 102.5 x 34	9 Dec. 2014
	11	FY14 Concrete Cutting Refinement	104 x 109 x 34	22 Aug. 2014
4	12	FY14 Concrete Cutting Refinement	102.5 x 108.5 x 34	3 Dec. 2014
	13	FY14 Concrete Cutting Refinement	104.5 x 111.5 x 34	3 Dec. 2014
	14	FY14 Concrete Cutting Refinement	104 x 109 x 34	6 Nov. 2014
5	15	FY14 Concrete Cutting Refinement	104 x 104 x 34	22 Dec. 2014
	16	FY14 Concrete Cutting Refinement	102.5 x 108.5 x 34	4 May 2015
	17	FY14 Concrete Cutting Refinement	104.5 x 111.5 x 34	4 May 2015

[a] Repair repeated.

Series 1 repairs were conducted in the FY13 Saw-Cutting Technologies Test Section (Repairs 1 and 2) and in the FY12 Precast Panel Test Section (Repairs 3, 4, and 5) in November 2013. Locations of the repairs are shown in Figure 1 and 2.

As shown in Table 3, Repairs 4 and 5 were repeated in March 2014 in the FY12 Marginal Materials Test Section (Figure 3). The long time frame between repairs and the repeat repairs was due to a heavy rain received between November 2013 and mid-March 2014. Immediately following the failure of these original repairs, portions of the caps were saw cut and removed. Examination of the subgrade revealed that the repairs failed prematurely due to poor drainage of the test section, as indicated by 6 in. of saturated material under the cap of Repairs 4-1 and 5-1. Dynamic cone

penetrometer (DCP) tests revealed CBR measurements in the base/subgrade of 2 percent for these repairs to a depth of 8 to 10 in. Standing water was also noted in the grassy area surrounding the corner of the test section where the repairs were made, confirming that drainage was an issue for this portion of the test section. For clarity, the original repairs are noted in this report as Repairs 4-1 and 5-1. The repeat repairs are noted as Repairs 4-2 and 5-2. Their locations are shown in Figure 3.

2.3.2 Series 2 repairs

In the second series of repairs, the cap thickness was increased over a moderately strong, but thin, base. Three increasing rapid-setting cap thicknesses were used (6, 8, and 10 in.) over 6-in.-thick crushed limestone base layers (target 50 CBR). The performance data were used to determine whether there was any benefit in adding a thin base layer beneath the various cap thicknesses and to develop a second design performance curve over a thin, but moderately strong, foundation.

Series 2 repairs were conducted in the FY14 Concrete Cutting Refinement Test Section (Repairs 6, 7, and 8) in July 2014 (Figure 4). Repair 7 was repeated in December 2014 due to heavy spalling adjacent to the repair's east edge caused during the saw-cutting preparation of the repair area. The increase in performance for this cap thickness (8 in.) was also comparatively less than that achieved by adding a 6-in.-thick base to the other repairs in this series, as described in Chapter 4. As a result, this repair was repeated as Repair 7-2 in the same test section as the original repair but in a new location, as shown in Figure 4. Details of repair distresses noted during trafficking are provided in Chapter 4.

2.3.3 Series 3 repairs

In the third series of repairs, the caps were placed over a strong, but thin, base. The rapid-setting cap thicknesses used in Series 2 (6, 8, and 10 in.) were repeated for Series 3, but they were placed over 6-in.-thick, dry-placed flowable fill base layers (target 100 CBR). The performance data were used to determine what effect a strong, thin base beneath these cap thicknesses would have on the repair life and to develop a third design performance curve.

Series 3 repairs were conducted in the FY14 Concrete Cutting Test Section (Repairs 9, 10, and 11) in August 2014 (Figure 4). The same repair areas

used for Series 2 repairs were utilized for Series 3 repairs. Prior to Series 3 repairs, the Series 2 repairs were removed by breaking the cap material and excavating the base material. Additionally, the east edge of each repair was saw cut to remove spalled areas in the parent PCC slabs noted during Series 2 trafficking. These saw cuts resulted in a slight increase in the repair widths (6 in.), as shown in Table 3.

Repair 10 was repeated as Repair 10-2 in December 2014 because during early trafficking efforts, the repair cap broke into several sections (shattered) after approximately 560 passes. Because this distress was not noted for Series 1 or Series 2 repairs for 8-in.-thick caps over weaker foundations, additional testing was required to determine whether the placement procedure (described in Chapter 3) of allowing the flowable fill to cure overnight prior to capping contributed to the distress. Details of repair distresses noted during trafficking are provided in Chapter 4. The repair was completed in the same test section as the original repair but in a new location (Figure 4).

2.3.4 Series 4 repairs

In the fourth series of repairs, the three cap thicknesses (6, 8, and 10 in.) were placed over 12-in.-thick flowable fill base layers. The base material was the same cementitious flowable fill material used for Series 3 repairs with a target CBR of 100 percent. The performance data were used to determine what effect a thicker, strong base beneath 6-, 8-, and 10-in.-thick cap thicknesses would have on the repair life and to develop a fourth design performance curve. Series 4 repairs were conducted in the FY14 Concrete Cutting Refinement Test Section (Repairs 12, 13, and 14) in the locations shown in Figure 4 during November and December 2014.

2.3.5 Series 5 repairs

In the final series of repairs, the three cap thicknesses (6, 8, and 10 in.) were placed over 12-in.-thick crushed limestone base layers. The base material was the same material used for Series 2 repairs with a target CBR of 50 percent. The performance data were used to determine what effect a thicker, moderately strong base beneath these cap thicknesses would have on the repair life and to develop a fifth design performance curve. Series 5 repairs were conducted in the FY14 Concrete Cutting Refinement Test Section (Repairs 15, 16, and 17) in the locations shown in Figure 4 during

December 2014 and May 2015. A wet winter and spring resulted in a delay for completing the Series 5 repairs.

2.4 Traffic simulation

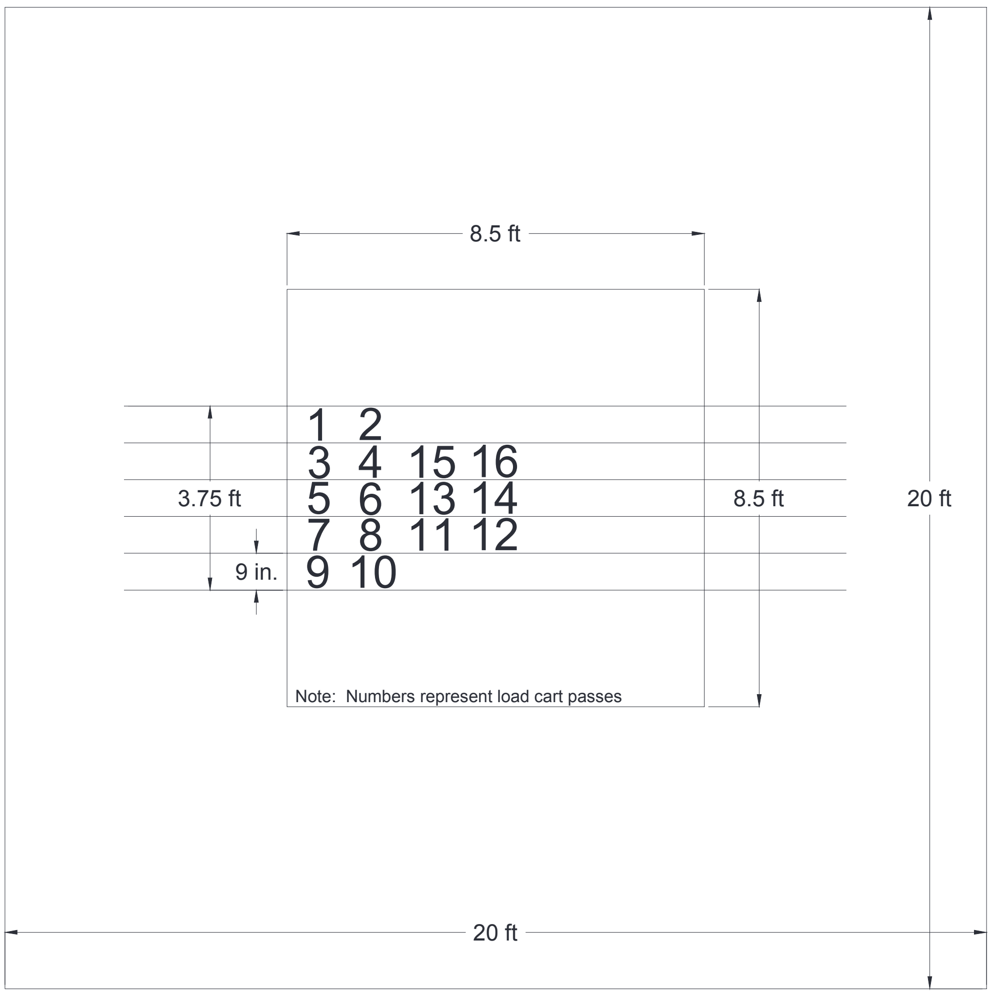
The F-15E military fighter jet aircraft was selected for traffic simulation in this study. This aircraft is considered to be one of the most damaging in the USAF inventory to pavement surfaces because of its small footprint and high tire pressure. All repairs were trafficked with a specially designed single-wheel load cart (Figure 5) to simulate this aircraft's traffic. The load cart was loaded to approximately 35,235 lb with a 325-psi tire pressure, which is within the normal range of loads expected during flight operations. During testing, the tire pressure was monitored using a tire pressure gauge and was adjusted if necessary.

Figure 5. F-15E load cart.

A simulated normally distributed traffic pattern was applied to the pavement repairs in a 3.75-ft-wide traffic area, as shown in Figure 6. Lanes were designed to simulate the traffic distribution pattern, or wander width, of the main landing gear wheels when taxiing to and from an active runway. The width of each lane corresponded to the contact width, 9 in., of the F-15E tire when fully loaded and not to the overall published tire width of 11 in. The normally distributed traffic pattern was simplified for ease of use by the load cart operator. Traffic was applied bi-directionally by

driving the load cart forward and then backward over the length of the repairs and then shifting the path of the load cart laterally approximately one tire width on each forward path. This procedure was continued until one pattern of traffic was completed. For the F-15E test area, one pattern resulted in 16 passes and four coverages.

Figure 6. F-15E traffic pattern on repair.



Trafficking operations began approximately 2 hr after the completion of each series of repairs and were continued until failure occurred or 10,000 passes were completed. Following 10,000 passes, trafficking was discontinued due to time and resource constraints.

2.5 Failure criteria

The pavement repairs were expected to fail because of surface deterioration of the rapid-setting cap under traffic. Visual inspections were

performed at selected traffic intervals to identify specific pavement distresses associated with a high foreign object damage (FOD) or tire hazard potential. Distresses were monitored in accordance with traditional condition survey procedures. Structural failure of the concrete pavement was defined as the identification of any of the following distresses: high-severity shattered slabs, cracks, or corner breaks measured by using the pavement condition index (PCI) inspection procedure (ASTM D5340). If high-severity corner or repair joint spalls occurred, then the repair was considered functionally failed. Spalling severity was based on the presence of fragmented pieces that might cause FOD or the extent to which the removed pieces of spalled material might cause tire damage hazards. High-severity joint spalls were defined by using their dimensions after FOD was removed.

Typical distresses observed in previous experiments with rapid-setting concrete capped repairs included cracking, spalling, shrinkage cracks, linear cracks, and shattered slabs. Cracking was considered a minor distress unless it resulted in the development of associated spalls with an accumulation of loose debris or in crack widths greater than or equal to 1 in. Spalled materials have the potential to be ingested into jet engines or to damage propellers and rotors of aircraft. Additionally, spalled concrete and wide cracks present tire hazards due to the potential of the sharp edges to cut aircraft tires. The concrete repairs were considered failed when distresses posing high FOD potential or tire hazards were identified. For comparative analysis of each repair, failure for this project was quantitatively defined by high-severity shattered slab or spalling greater than 2 ft long, 6 in. wide, and 2 in. deep across 50 percent of the spall length. As FOD was produced during trafficking, it was removed to prevent tire hazards. Loose material in spalls was removed if it could easily be dislodged by hand or broom. An example of a joint spall presenting high tire hazard potential is shown in Figure 7.

2.6 Data collection

Prior to trafficking, the surface of each repair was inspected for any pre-traffic distresses. After 112 passes, the surface of each repair was inspected again. The repairs were then inspected at 500- to 1,000-pass intervals until they failed or until 10,000 passes were completed. Cracks were marked using paint crayons, and photographs were taken to document the crack/failure progression. Each repair was also surveyed by using a rod and level prior to trafficking and at 1,000-pass intervals. The survey data were used to measure any permanent deformation that occurred.

Figure 7. Joint spall presenting high FOD (swept) and tire damage potential.

3 Repair Procedures

The same general procedure was used for all repairs, including saw cutting to establish repair boundaries, concrete pavement breaking, sublayer excavation, sublayer material placement, and rapid-setting concrete cap placement. Each task was accomplished over a period of several days for each sequence of repairs. This chapter briefly describes the repair processes used for each series of repairs.

3.1 Saw cutting

The boundaries of each repair were saw cut with a Caterpillar 279C compact terrain loader (CTL), also known as a skid steer, with an SW60 wheel saw attachment. This equipment had been previously identified as suitable for expedient cutting operations in ADR scenarios, and equipment details are described by Edwards et al. (2013). The CTL was used to conduct full-depth saw cuts through the PCC. A single CTL was used to produce approximate repair sizes of 8.5 ft by 8.5 ft. Two persons were utilized to complete saw-cutting activities: a CTL operator and a spotter. Figure 8 shows the CTL with the wheel saw cutting out a repair area, and Figure 9 shows a typical repair area after saw cutting.

Figure 8. Saw-cutting repair area using CTL and wheel saw.

Figure 9. Typical saw-cut repair area.

3.2 Concrete breaking

Following saw-cutting activities, the PCC within the saw-cut boundaries was broken using the CTL with an Atlas SBC410-II pavement-breaker attachment and/or a Volvo Ec210CL excavator with a Kent (3,000 lb) hammer attachment. The Volvo excavator and hammer attachment were required to break PCC slabs that were thicker than 14 in., such as the FY14 Concrete Cutting Refinement Test Section. Two persons were utilized to complete breaking operations, an operator and a spotter, to ensure that the operator did not damage the parent PCC slabs. Figure 10 presents the breaking of the PCC surface, while Figure 11 shows the broken PCC.

Figure 10. Breaking PCC using CTL (left) and excavator (right) with breaker attachments.

Figure 11. Broken PCC.

3.3 Sublayer excavation

Following breaking activities, each repair was excavated to remove the broken PCC and underlying material to the target subgrade depth of approximately 34 in. Either a Bobcat 442 compact excavator with bucket attachment or a Volvo EC210CL excavator with a 36-in. bucket attachment were used to excavate each repair. The Volvo excavator was required to remove the broken concrete debris from within the boundaries when the PCC pavement was more than 14 in. thick. An equipment operator and a spotter were utilized to complete excavation activities. Figure 12 shows the excavating process.

Figure 12. Excavating repair with compact excavator.

3.4 Sublayer material placement

Following the excavation of the repair, the existing silty clay (CL) subgrade material was replaced with a silt material obtained from a local source. The material was placed in 6- to 8-in.-thick lifts and compacted with a jumping jack compactor (Figure 13) to a target subgrade strength of 4 to 6 CBR. On average, 12 to 18 in. of subgrade material was replaced before the base or PCC placement.

Figure 13. Compaction of subgrade (left) and limestone base (right).

If the repair included a base layer, then the base material was placed until the target elevation for cap placement was achieved. For limestone placement, the base layers were compacted in 3- to 4-in.-thick lifts and compacted using two coverages of the plate compactor (Figure 13) to reach a target strength of 50 CBR. Two technicians were used for compacting the limestone: a CTL operator and a compactor operator, who was also used as a spotter. For placing the flowable fill, an extendable boom forklift was used to lower the super sack over the repair void, and the material was dispensed directly into the excavation in 3- to 4-in.-thick lifts. Approximately 40 gal of water per lift was dispensed over the surface of each lift by using a water truck, a 2-in.-diameter hose, and a flow meter. This process was repeated until the target backfill depth was achieved. For the final lift of flowable fill, typically only 30 to 35 gal of water was dispensed to reduce the amount of standing water on the surface of the flowable fill. Large amounts of standing water could have affected the consistency of the overlying rapid-setting concrete during placement.

Figure 14 shows the placement process. Four persons were utilized to complete flowable fill backfill operations: a forklift operator, two spotters, and a water truck operator. For Series 3 repairs, the flowable fill was

placed 18 to 24 hr prior to the cap placement. For the repeat Series 3 repair and Series 5 repairs, flowable fill was placed immediately prior to the cap placement.

Figure 14. Flowable fill placement, clockwise from top left: dispensing dry material, checking depth, adding water, and completed base.

3.5 Rapid-setting cap placement

Following the placement of the foundation materials, each repair was capped with CTS Rapid Set Concrete Mix®. A simplified volumetric mixer, factory calibrated for the repair material and manufactured by CemenTech Inc. (www.cementech.com), was used for all repair capping activities. Prior to each repair, typically four 3,000-lb supersacks of the rapid-setting concrete mix were loaded into the volumetric mixer. Each water tank on the simplified volumetric mixer was also filled during this time with approximately 250 gal of water. If needed (temperatures above 85°F), approximately 12.5 lb of citric acid was added to each water tank.

Before placement of the concrete cap, the repair void, including the saw-cut faces and sublayer material, was dampened by using the pressure washer attachment to the mixer. The rapid-setting concrete was then dispensed directly into the repair void. Once the repair was filled, the concrete cap was screeded once with an aluminum screed. With hand trowels, minimal finishing was applied to the surface of the repairs if required. Care was made to clean the excess material from around the repair area to prevent FOD. Figure 15 shows the placement of the rapid-setting concrete cap using the simplified volumetric mixer, and Figure 16 shows the cap after screeding was completed.

Figure 15. Placing rapid-setting concrete cap.

Figure 16. Completed rapid-setting concrete cap.

Four to six people were utilized for capping including a vehicle operator, mixer operator, and two to four additional personnel for screeding, sample preparation, and cleanup. Each repair cap was allowed to cure for approximately 2 hr prior to the application of traffic. This cure time had previously been identified for expedient repair efforts with this material (Priddy 2011).

3.6 Quality assurance tests

Several tests were conducted to ensure that each repair layer was constructed to its target layer thickness and that similar subgrade and base strengths were achieved between repairs. This included semi-destructive testing of the sublayer materials, nuclear gauge testing, preparing concrete samples during capping, and surveying the surface of each repair layer.

3.6.1 Dynamic cone penetrometer (DCP)

After compaction of the subgrade, three DCP tests were conducted to determine the DCP-estimated CBR values for the subgrade following the procedure described by ASTM D6951 (2003). The CBR value ranges from 0 to 100 percent, and a CBR value of 100 percent is equivalent to the bearing capacity of a compacted, dense-graded, crushed aggregate. After compaction of the base, three additional DCP tests were conducted to determine the strength of the base material. Results of DCP testing prior to trafficking are presented in Table 4.

The DCP was not able to accurately estimate the strength of the limestone base layer of the Series 2 and Series 5 repairs due to lack of confinement at the top of the testing layer. For a course-grained material such as the limestone base used in this test section, Webster et al. (1994) determined that a 5-in.-minimum penetration depth was required before the actual strength of the surface soil layer could be determined with the DCP. Thus, the DCP could not be used to accurately estimate the limestone base layers' strength, particularly with Series 2 repairs, because the base layer was only 6 in. thick. The crushed limestone base layers of the Series 5 repairs were 12 in. thick, so only the DCP data from the bottom 6 to 7 in. of the material was used to estimate CBR. While the DCP-estimated CBRs for Series 2 and 5 repairs are presented in Table 4, the actual CBR of the crushed limestone material is assumed to be 50 CBR or higher based on the dry density results from the nuclear density gauge (presented in Section 3.6.2) on the material and previous experiences with this material.

Table 4. Average CBR data of sublayers measured using DCP prior to trafficking.

Series No.	Repair No.	Cap Thickness (in.)	Base Material	Base Thickness (in.)	Avg. Base CBR (%)	Subgrade Material	Avg. Subgrade CBR (%)
1	1	6	none	0	-----	silty clay	4
	2	8	none	0	-----	silty clay	4
	3	10	none	0	-----	silty clay	7
	4-1	12	none	0	-----	silty clay	4
	4-2	12	none	0	-----	silty clay	4
	5-1	14	none	0	-----	silty clay	4
	5-2	14	none	0	-----	silty clay	6
2	6	6	GW	6	30	silty clay	4
	7-1	8	GW	6	30	silty clay	5
	7-2	8	GW	6	34	silty clay	6
	8	10	GW	6	20	silty clay	6
3	9	6	flow fill	6	84	silty clay	6
	10-1	8	flow fill	6	81	silty clay	5
	10-2	8	flow fill	6	86	silty clay	4
	11	10	flow fill	6	80	silty clay	6
4	12	6	flow fill	12	98	silty clay	5
	13	8	flow fill	12	100	silty clay	5
	14	10	flow fill	12	100	silty clay	5
5	15	6	GW	12	40	silty clay	5
	16	8	GW	12	30	silty clay	4
	17	10	GW	12	30	silty clay	5

After trafficking of each repair was completed, three additional DCP tests were conducted to determine whether any changes in foundation strength occurred. Forensic DCP tests were conducted by coring or drilling through the Rapid Set Concrete Mix® cap and testing with the DCP through the base and subgrade layers. Results of DCP tests conducted after trafficking are presented in Chapter 4.

3.6.2 Nuclear density gauge tests

Table 5 shows the results of nuclear density gauge tests for each constructed layer. The soil base and subgrade layers were tested with the nuclear density gauge at three different test points within each repair. The gauge was then turned 90 degrees at each test location for a second measurement at the same test point.

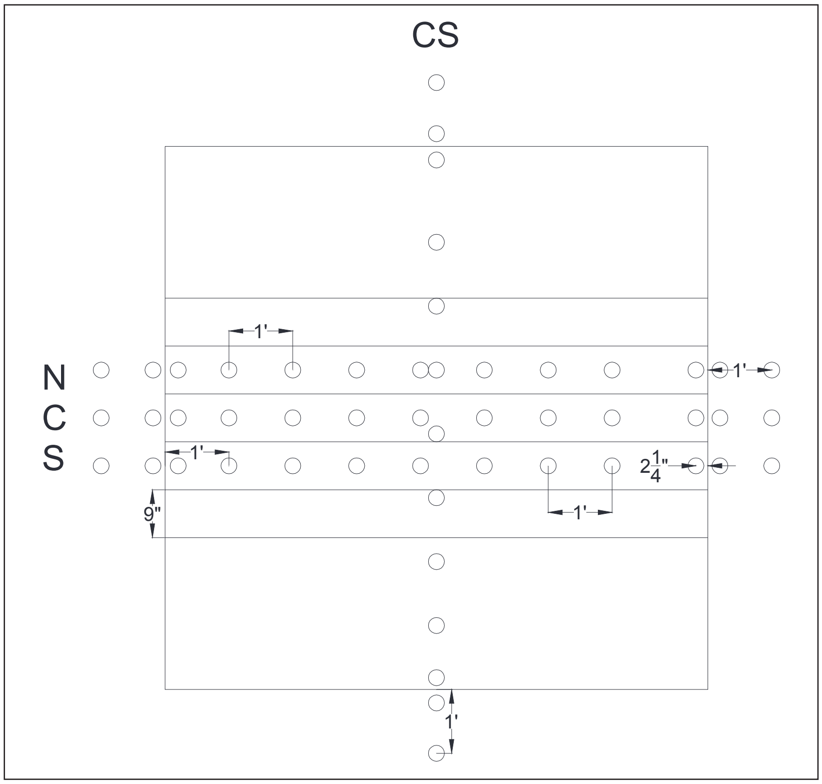
Table 5. Nuclear density gauge-measured layer properties as constructed.

Series No.	Repair No.	Base					Silty Clay Subgrade		
		Thickness (in.)	Material	Average Moisture (%)	Average Dry Density (pcf)	Average Wet Density (pcf)	Average Moisture (%)	Average Dry Density (pcf)	Average Wet Density (pcf)
1	1	0	none	-----	-----	-----	7.2	93	100
	2	0	none	-----	-----	-----	11.9	94	105
	3	0	none	-----	-----	-----	17.5	103	121
	4-1	0	none	-----	-----	-----	15.3	103	119
	4-2	0	none	-----	-----	-----	15.1	101	117
	5-1	0	none	-----	-----	-----	15.0	100	115
	5--2	0	none	-----	-----	-----	15.0	102	116
2	6	6	GW	3.2	124	127.6	12.0	86	97
	7-1	6	GW	3.7	124	125.5	12.8	93	105
	7-2	6	GW	4.9	136	142.0	17.2	107	125
	8	6	GW	3.6	121	125.6	12.7	91	103
3	9	6	flow fill	-----	-----	-----	17.3	95	111
	10-1	6	flow fill	-----	-----	-----	19.6	101	121
	10-2	6	flow fill	-----	-----	-----	16.9	103	121
	11	6	flow fill	-----	-----	-----	19.5	99	118
4	12	12	flow fill	-----	-----	-----	15.7	106	122
	13	12	flow fill	-----	-----	-----	15.9	106	123
	14	12	flow fill	-----	-----	-----	18.1	104	123
5	15	12	GW	3.9	133	138	16.4	106	123
	16	12	GW	4.2	131	136	17.3	110	128
	17	12	GW	4.4	130	136	16.2	111	128

3.6.3 Surveying

A rod and level were used to verify that the target layer thicknesses for each sublayer and the repair caps were achieved. Surveying was accomplished within the repair area, as shown in Figure 17. Three lines of points were collected in the direction of traffic on each repair: they are labeled N, C, and S for north, center, and south, respectively, and CS for the cross-section measurements. As shown in Figure 17, additional data were collected at the repair joints to determine elevation changes at the joint due to removal of spalled material during trafficking. Layer thickness values for each repair are presented in Table 6. All pavement layers were constructed within 0.5 in. of the target thicknesses.

Figure 17. Location of survey points.



3.6.4 Laboratory testing of field-collected samples

Laboratory testing of field-collected samples on the fresh rapid-setting concrete was conducted to determine whether any differences in PCC quality occurred between repairs. Large differences in material quality between repairs could impact the performance of the repairs under trafficking.

During placement of each repair cap, three test specimens were prepared for UCS tests in accordance with ASTM C39 (2010). The UCS test is a relatively simple test used to determine the strength of the concrete for quality assurance purposes. The compressive strength is the measure of the concrete's resistance to crushing. The higher the compressive strength, the less likely a material is to be crushed under tire loads. Three 3-in.-diam by 6-in.-long cylinders were prepared from each repair in accordance with ASTM C31 (2015) and were allowed to cure for 28 days at ambient temperature prior to testing. Figure 18 shows the preparation of compressive cylinders.

Table 6. Target and actual layer thicknesses.

Series No.	Repair No.	Concrete Cap: Target Cap Thickness (in.)	Concrete Cap: Average Cap Thickness (in.)	Base: Base Material	Base: Target Base Thickness (in.)	Base: Average Base Thickness (in.)
1	1	6.0	5.6	none	-----	-----
	2	8.0	7.8	none	-----	-----
	3	10.0	10.5	none	-----	-----
	4-1	12.0	12.1	none	-----	-----
	4-2	12.0	12.4	none	-----	-----
	5-1	14.0	14.1	none	-----	-----
	5-2	14.0	14.3	none	-----	-----
2	6	6.0	6.4	GW	6.0	6.1
	7-1	8.0	8.0	GW	6.0	6.0
	7-2	8.0	8.2	GW	6.0	6.1
	8	10.0	9.8	GW	6.0	6.2
3	9	6.0	5.6	flow fill	6.0	6.5
	10-1	8.0	7.5	flow fill	6.0	6.5
	10-2	8.0	7.9	flow fill	6.0	6.4
	11	10.0	10.0	flow fill	6.0	6.3
4	12	6.0	6.0	flow fill	12.0	12.5
	13	8.0	8.0	flow fill	12.0	12.2
	14	10.0	10.1	flow fill	12.0	12.2
5	15	6.0	6.0	GW	12.0	11.7
	16	8.0	8.1	GW	12.0	11.8
	17	10.0	9.8	GW	12.0	12.2

In addition to resisting crushing forces, concrete must resist bending or flexural forces. The measure of the concrete’s resistance to flexural forces is called flexural strength. This property is used for rigid pavement design and evaluation, but it is often estimated from compressive strength because compressive strength requires less material to prepare samples for laboratory testing. Airfield quality PCC generally has a compressive strength of 5,000+ psi, which correlates to a flexural strength of 650+ psi.

Figure 18. Preparation of compressive cylinders.

The same samples used for UCS testing were used to determine the modulus of elasticity (MOE) for the repairs in accordance with procedures detailed in ASTM C469 (2014). MOE is used for pavement design purposes, thus this property was measured. Airfield quality PCC generally has an MOE of 4 to 5 million psi.

The concrete slump for each repair cap was determined in accordance with ASTM C143 (2012). Slump is a measure of consistency, or relative ability of the concrete to flow. If the slump is too low, then the concrete is unable to flow, causing potential problems with placement and consolidation. For CTS Rapid Set Concrete Mix®, if the slump is too low, then the material cannot be placed before it sets. Conversely, if the slump is too high, which means the concrete flows too freely, there are potential problems with segregation. Previous field tests have shown that CTS Rapid Set Concrete Mix® can be placed with less physical effort and minimal segregation at slumps between 7 and 10 in. with minimal impact to the repair performance and early compressive strength values. Slump flow (ASTM C1611 2014) is also a measure of the ability of the concrete to flow and is often used for flowable fill materials. Figure 19 shows measuring the slump of the rapid-setting concrete material.

Figure 19. Measurement of slump.

The laboratory test results are presented in Table 7. In some situations, either the slump or slump flow could not be measured due to the material's rapid hardening during the preparation of the collected material. Due to the rapid speed of placement of material in each repair (approximately 6 min), another sample could not be collected for testing. The priority for sampling was the preparation of the UCS/MOE cylinders.

Review of the rapid-setting concrete mechanical properties indicated that average UCS results for each repair exceeded normal airfield quality PCC UCS results of 5,000+ psi. The UCS for the rapid-setting concrete repairs ranged from 6,690 to 9,890 psi, while the average UCS for all repairs was 8,500 psi. Review of the slump data and field observations indicated that despite a slump in excess of 9.5 in. for some of the Series 1 repairs, no decrease in 28-day UCS was below 5,000 psi. The average MOE results for all repairs was 4.6 million psi, which is within the normal range for airfield quality PCC. No correlation of the data presented in Table 7 exists between UCS, slump flow, and MOE.

Table 7. Results of laboratory testing and field testing.

Series No.	Repair No.	Slump (in.)	Slump Flow (in.)	UCS (psi)	Average Modulus of Elasticity (psi)
1	1	8.50	not measured	7,700	4.4×10^6
	2	9.25	not measured	8,580	4.5×10^6
	3	8.50	not measured	9,370	4.5×10^6
	4-1	8.75	not measured	7,990	4.5×10^6
	4-2	10.50	22.00	7,940	4.8×10^6
	5-1	10.25	22.00	8,730	4.6×10^6
	5-2	9.00	22.00	7,450	4.7×10^6
2	6	not measured	not measured	6,960	5.9×10^6
	7	not measured	not measured	7,520	4.5×10^6
	7-2	not measured	32.00	8,940	4.7×10^6
	8	not measured	not measured	7,190	4.3×10^6
3	9	not measured	20.00	8,600	4.4×10^6
	10-1	not measured	25.00	8,330	4.6×10^6
	10-2	not measured	27.00	9,350	4.7×10^6
	11	not measured	20.00	9,040	4.6×10^6
4	12	not measured	26.00	not measured	not measured
	13	not measured	23.00	9,890	not measured
	14	not measured	19.00	8,490	4.6×10^6
5	15	not measured	26.00	9,100	4.6×10^6
	16	not measured	not measured	9,610	not measured
	17	not measured	19.00	9,240	not measured

4 Repair Performance Results

Table 8 presents the overall results of the F-15E traffic operations. As mentioned previously, trafficking was discontinued after 10,000 passes if failure had not occurred. The following sections describe the results for each series of repairs, including the surface distresses and pavement structure forensics.

Table 8. General results of traffic tests over rapid-setting crater repairs.

Series No.	Repair No.	Cap Thickness (in.)	Base Material	Base Thickness (in.)	Passes to Failure[a]	Failure Mode
1	1	6	none	----	560	length, width, and depth of spall
	2	8	none	----	1,750	length, width, and depth of spall
	3	10	none	----	3,000	length, width, and depth of spall
	4-1[b]	12	none	----	3,000	length, width, and depth of spall
	4-2	12	none	----	9,000	length, width, and depth of spall
	5-1[b]	14	none	----	2,500	length, width, and depth of spall
	5-2	14	none	----	10,000+	close to failure due to length, width, and depth of spall
2	6	6	GW	6	1,290	tire hazard and FOD
	7-1[c]	8	GW	6	2,500	depth of spall and tire hazard
	7-2	8	GW	6	3,500	tire hazard; length and width of spall; depth was 1.9 in.
	8	10	GW	6	10,000+	---------
3	9	6	flow fill	6	3,900	length, width, and depth of spall
	10-1[d]	8	flow fill	6	10,000+	---------
	10-2	8	flow fill	6	10,000+	---------
	11	10	flow fill	6	10,000+	---------
4	12	6	flow fill	12	10,000+	---------
	13	8	flow fill	12	10,000+	---------
	14	10	flow fill	12	10,000+	---------
5	15	6	GW	12	1,508	length, width, and depth of spall
	16	8	GW	12	8,000	length, width, and depth of spall
	17	10	GW	12	8,500	length, width, and depth of spall

[a] Failure defined as high-severity shattered slab or spalls > 2 ft long, > 6 in. wide, and > 2 in. deep; traffic stopped at 10,000 passes

[b] Repair repeated due to wet conditions noted after failure

[c] Repair repeated due to early failure of the repair

[d] Repair repeated due to low-severity shattered slab occurring at 560 passes

4.1 Post-traffic DCP results

DCP tests were conducted following the failure of each repair or after the completion of 10,000 passes. Results of post-traffic DCP tests are presented in Table 9.

Table 9. CBR post traffic values as measured using the DCP.

		Base			Silt Subgrade
Series No.	Repair No.	Thickness (in.)	Material	Average CBR (%)	Average CBR (%)
1	1	0	none	-----	no data
	2	0	none	-----	no data
	3	0	none	-----	5
	4-1	0	none	-----	2
	4-2	0	none	-----	4
	5-1	0	none	-----	2
	5--2	0	none	-----	4
2	6	6	GW	51	4
	7-1	6	GW	46	4
	7-2	6	GW	45	9
	8	6	GW	68	6
3	9	6	flow fill	100	15
	10-1	6	flow fill	100	15
	10-2	6	flow fill	100	8
	11	6	flow fill	100	14
4	12	12	flow fill	100	12
	13	12	flow fill	100	15
	14	12	flow fill	100	13
5	15	12	GW	49	11
	16	12	GW	39	10
	17	12	GW	52	12

Post-traffic DCP tests revealed that Series 1, Repairs 4-1 and 5-1 had an average CBR of 2 percent. This indicates that water may not have been able to drain from beneath Repairs 4-1 and 5-1 and that moisture entering through periods of heavy rain most likely attributed to their early failure.

Review of the post-traffic DCP data also show an increase in strength between the pre- and post-traffic for the flowable fill material for Series 2.

In most cases, refusal of the device (CBR of 100 percent) in flowable fill occurred after trafficking was completed, indicating that the material had gained additional strength following its placement. DCP tests had been conducted approximately 18 hr after initial placement and prior to placing the rapid-setting caps, with average CBR values ranging from 80 to 84 percent. This agrees with previous laboratory results showing 100 CBR after 24 hr of cure time. The subgrades for Series 2 also increased in CBR from 5 to 9 percent to 12 to 18 percent. This indicates that the subgrade dried during the trafficking period. These repairs were conducted during the summer months when temperatures were higher and rainfall was minimal (see Table 3).

4.2 Surface distresses

4.2.1 Series 1 repairs

The Series 1 repairs, consisting of varying rapid-setting concrete cap thicknesses over subgrade, withstood varying levels of traffic prior to failing. The main mode of failure for all repairs was spalling along the transverse joints (joints perpendicular to the direction of travel). Minor distresses, such as shrinkage cracks, were noted prior to traffic for many of the repairs. The shrinkage cracks did not appear to contribute to the repair failures. Distresses noted during trafficking for each Series 1 repair are shown in Appendix A (Table A1). Since spalling produces FOD, the overall FOD potential for the repairs was also monitored and is included in Table A1.

Repair 1, with a 6-in.-thick concrete cap, failed at approximately 560 passes. Repairs 2 and 3, with 8- and 10-in.-thick caps, respectively, withstood approximately twice the number of passes with each additional 2 in. of rapid-setting concrete added to the surface. Figure 20, 21, and 22 show Repairs 1, 2, and 3, respectively, at failure.

Figure 20. Series 1, Repair 1 - west edge at failure (560 passes).

Figure 21. Series 1, Repair 2 - overall at failure (1,750 passes).

Figure 22. Series 1, Repair 3 - overall at failure (3,000 passes).

Repair 5-1, the thickest repair in this series, failed prior to Repairs 3 and 4-1. As mentioned previously, post-traffic DCP tests revealed that Repairs 4-1 and 5-1's subgrades had average CBRs of 2 percent, which was weaker than before traffic began. Therefore, the repairs were repeated in another location as Repairs 4-2 and 5-2. As shown in Table 8, Repair 4-2 withstood 6,000 more passes than Repair 4-1, and Repair 5-2 was able to support 10,000 passes without failing.

4.2.2 Series 2 repairs

The Series 2 repairs, consisting of a 6-in.-thick limestone base with different cap thicknesses, withstood varying levels of traffic prior to failing. The Series 2 repairs were the only repairs that developed spalling along all four joints, rather than only the trafficked joints. This is likely due to excessive hand-finishing occurring at the joints during construction. Surface distresses noted during trafficking for each Series 2 repair are shown in Table A2.

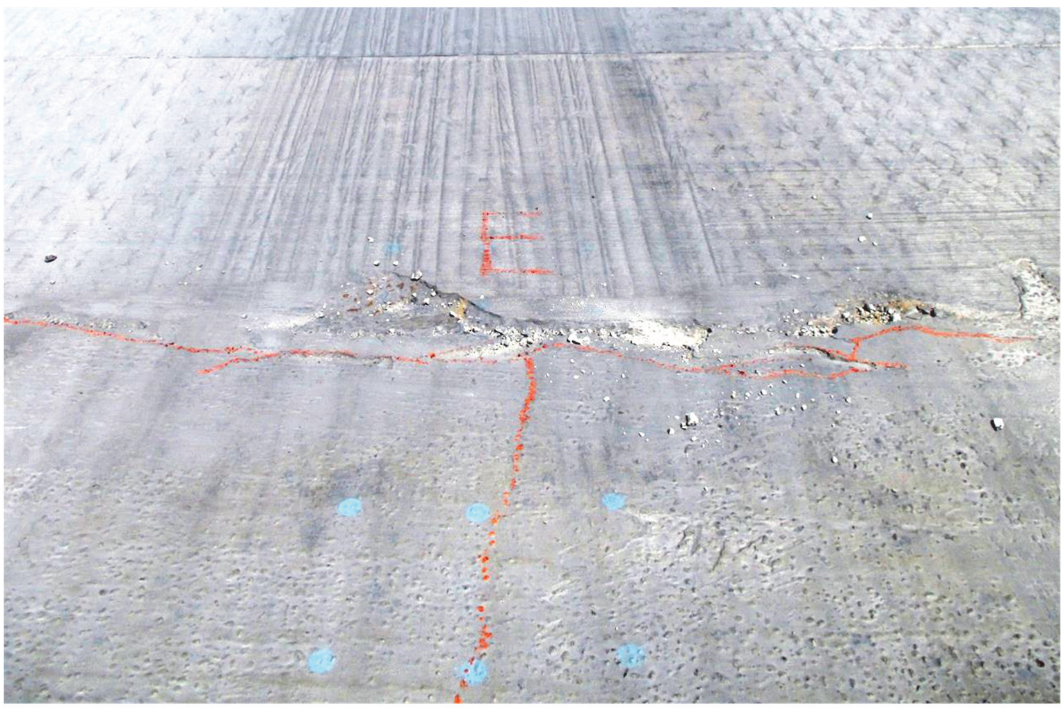
Repair 6 trafficking efforts were discontinued after 1,300 passes due to the surface spalling along a trafficking joint having a sharp edge, creating a tire hazard for the F-15E load cart (Figure 23). The spall was 0.75 in. deep and 6 in. wide. Also, the FOD in and around the spall had maximum size pieces of 1 in.

Figure 23. Series 2, Repair 6 - east edge at failure (1,300 passes).

The main mode of failure for Repairs 7-1 and 7-2 was spalling along the transverse joints (joints perpendicular to the direction of travel). Repair 7-1 likely failed prematurely after 2,500 passes due to the condition of the adjacent parent PCC along the east edge of the repair. The parent PCC was severely damaged during the repair process, with spalled areas approximately 6 in. by 6 in. and 0.125 in. deep prior to traffic. During the capping of this repair, rapid-setting concrete was used to partially patch these areas; however, the material quickly deteriorated during the first 500 passes and was not repaired during trafficking. Figure 24 shows the damaged area prior to capping and prior to trafficking. Failure occurred at 2,500 passes (Figure 25).

Figure 24. Spalled parent PCC for Series 2, Repair 7-1 - spalled areas on east edge (left) and partially filled spall prior to traffic (right).

Figure 25. Series 2, Repair 7-1 - overall at failure (2,500 passes).



Repair 7-1 was repeated as Repair 7-2 to determine whether the spalling of the parent PCC slab contributed to an increased spalling rate of the repair. Repair 7-2 traffic was stopped after the application of 3,500 passes due to a tire hazard. The depth and width of the largest spall were 1.875 and 8 in., respectively. It is likely the repair would have met the failure criteria after another 200 to 500 passes. The repeat repair lasted approximately 1,000 more passes than Repair 7-1.

Trafficking of Repair 8 was discontinued following 10,000 passes; however, the repair was close to failure with a maximum spall size of 93 in.

long, 6 in. wide, and 2 in. deep. It is anticipated that the repair would have withstood approximately 100 to 200 additional passes before the failure criteria were met. Figure 26 shows Repair 8 at 10,000 passes.

Figure 26. Series 2, Repair 8 - overall at 10,000 passes.

4.2.3 Series 3 repairs

The Series 3 repairs consisted of 6-, 8-, and 10-in.-thick rapid-setting concrete caps over 6 in. of rapid-setting flowable fill. Distresses noted during trafficking for each repair are described in Table A3.

Repair 9 failed under trafficking at 3,900 passes. The mode of failure for Repair 9 was spalling along the transverse joints. The maximum spall size was 62 in. long, 6.5 in. wide, and 2 in. deep. A few shrinkage cracks were noted prior to traffic; however, they had no effect on the repair failure. Figure 27 shows Repair 9's west edge at failure (3,900 passes).

Figure 27. Series 3, Repair 9 - west edge at failure (3,500 passes).

A low-severity shattered slab was noted at 560 passes on Repair 10-1. This did not occur during the Series 2 testing for the same cap thickness over a weaker base material. The shattered slab, however, did not progress in severity and did not result in the repair's failure. Because of the early instance of a shattered repair cap, Repair 10-1 was repeated as Repair 10-2. Repair 10-2 had shrinkage cracks, the longest of which was 46 in., over the repair before trafficking began. Repairs 10-1 and 10-2 were not failed following the application of 10,000 passes. Both repairs had minor spalling along the edges at 10,000 passes. Figure 28 shows the low-severity shattered slab of Repair 10-1 at 560 passes, and Figure 29 shows the Repair 10-1 at 10,000 passes.

Repair 11 was constructed the same day as Repair 10-1; however, Repair 11 did not have any surface distresses prior to trafficking. A low-severity corner break occurred after the application of 560 passes, and low-severity joint spalling began to develop along the trafficking edges around 4,000 passes. After the application of 10,000 passes, the east edge had a low-severity spall 63 in. long, 2 in. wide, and 0.5 in. deep. Figure 30 shows Repair 11 at 10,000 passes.

Figure 28. Series 3, Repair 10-1 - low-severity shattered slab at 560 passes.

Figure 29. Series 3, Repair 10-1 - not failed at 10,000 passes.

Figure 30. Series 3, Repair 11 - not failed at 10,000 passes.

4.2.4 Series 4 repairs

The Series 4 repairs, consisting of Rapid Set Concrete Mix® caps over 12 in. of cementitious flowable fill base material, withstood 10,000 passes of F-15E load cart traffic without failing. Detailed notes of the surface distresses identified during trafficking for the Series 4 repairs are presented in Table A4.

Repair 12 had a few shrinkage cracks develop along the north, west, and east edges shortly after construction. By 112 passes, more surface cracking occurred at all four corners, and the existing shrinkage cracks' lengths increased. Following the application of 10,000 passes, only one repair joint had low-severity spalling, which was 24 in. long, 1 in. wide, and 0.25 in. deep.

Repair 13 also had a few shrinkage cracks develop in the center of the repair and along the west edge before trafficking began. More cracks occurred around 112 passes, and spalling began to develop around 560 passes. By 10,000 passes, Repair 13 had deteriorated more than Repair 12. Both trafficked joints had spalling. The largest spall was 68 in. long, 2.5 in. wide, and 0.25 in. deep.

Repair 14 developed shrinkage cracks approximately 20 min after the repair was completed. By the time trafficking began over 2 hr later, shrinkage cracks covered the entire surface. All four corners had cracks around 560 passes; however, no new cracks formed, and the shrinkage cracks did not increase in size. After the application of 10,000 passes, the largest joint spall was 8 in. long and 2 in. wide (Figure 31).

4.2.5 Series 5 repairs

Series 5 repairs consisted of 6-, 8-, and 10-in.-thick caps over 12 in. of crushed limestone. Detailed notes of the surface distresses identified during trafficking for the Series 5 repairs are presented in Table A5.

After construction, Repair 15 developed six approximately 25-in.-long surface cracks that extended from the repair edges. After 800 passes, both trafficked joints had high-severity spalling (Figure 32). One spall along the west edge was 60 in. long, 5.5 in. wide, and 1.75 in. deep. The repair was failed after 1,508 passes due to the size of the spall along the west edge (Figure 33).

Repair 16 failed after 8,000 passes. Around 3,000 passes, cracking along the trafficked joints progressed into spalls, particularly along the east edge. By 6,000 passes, spalling along the east edge had increased to high severity. The joint spall spanned the length of the repair edge and was 9 in. wide and just under 1.5 in. deep. At 8,000 passes, Repair 16 was considered failed since the spalling along the east edge had exceeded the failure criteria.

Figure 31. Series 4, Repair 14 - after 10,000 passes.

Figure 32. Repair 15 spalling at 800 passes (after being swept).

Figure 33. Repair 15 at failure of 1,508 passes.

Repair 17 seemed to deteriorate at a rate similar to that of Repair 16. After 3,000 passes, the trafficked repair joints began spalling along the center 55 in. of each edge. By 7,000 passes, the spalls spanned the entire length of the repair along the west edge. At 8,500 passes, the maximum spall width and depth were 7.5 in. and just over 2 in., respectively.

4.3 Permanent deformation

During trafficking, the repairs were monitored for elevation changes by using a surveying rod and level in both the longitudinal (in the direction of traffic) and transverse directions (perpendicular to traffic) in the centers of each repair, as shown previously in Figure 17. The maximum measured changes in elevations are provided in Table 10. The maximum change in elevation was recorded for most cases along the edges of the repairs in the locations of spalls. The maximum change in elevation measured in the location of the spalls is less than that measured during the inspection process with a ruler due to the inability to place the rectangular rod in the deepest portions of the spalled areas, as recorded in the previous section. These data show that no settlement or faulting occurred with these repairs. Also, as shown in Table 10, two of the repairs had an elevation difference of more than 1.25 in., which could result in landing gear damage for the F-15E aircraft.

Table 10. Maximum elevation changes.

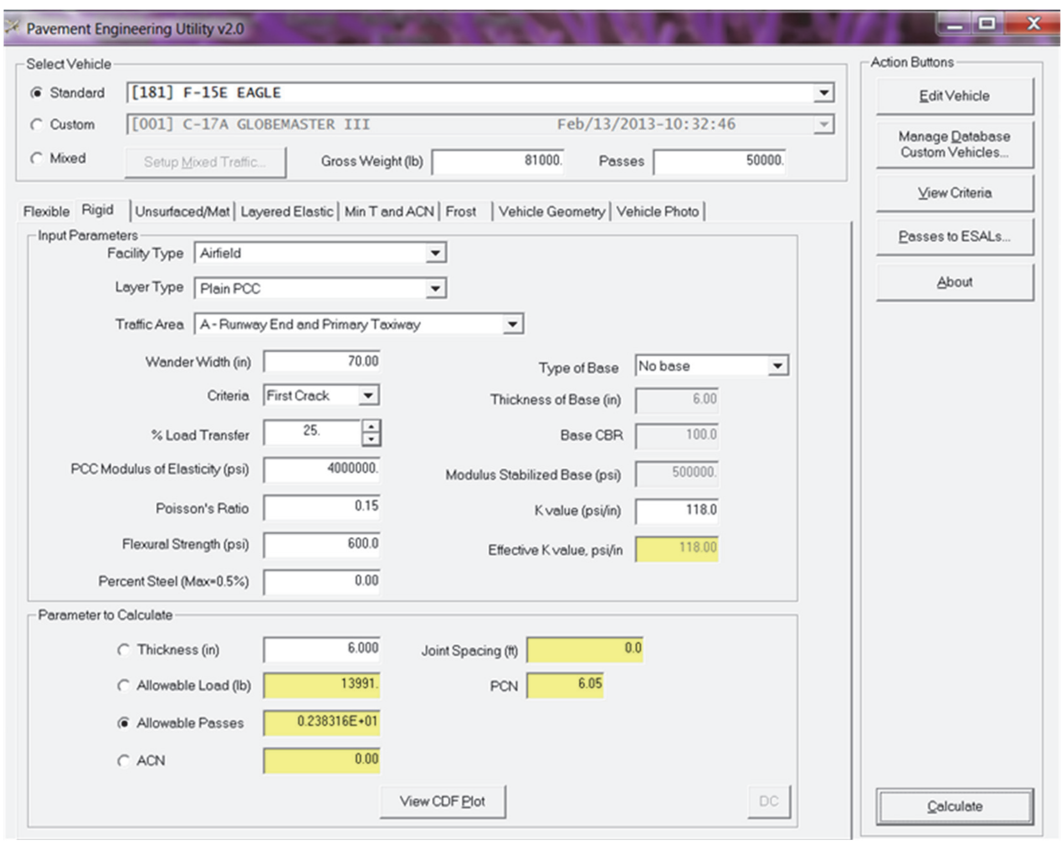
Series No.	Repair No.	Max Elevation Change (in.)	Location of Max Elevation Change
1	1	-0.72	west edge
	2	-1.32	east edge
	3	-0.24	north edge
	4-1	-0.48	north and south edges
	4-2	-1.44	east edge
	5-1	-0.12	north edge
	5-2	-0.36	east and west edges
2	6	-0.24	east edge
	7-1	-0.12	east edge
	7-2	-0.60	west edge
	8	-0.24	east edge
3	9	-0.84	west edge
	10-1	-0.36	east edge
	10-2	-0.12	east edge
	11	-0.36	west edge
4	12	-0.24	west edge
	13	-0.24	east and west edges
	14	-0.24	south edge
5	15	-0.48	west edge
	16	-0.84	east edge
	17	-0.84	west edge

5 Analysis and Discussion of Results

5.1 Predicted performance using design software

The pavement design software PSeven (Figure 34) was used to determine the theoretical design life for the Rapid Set repairs in terms of aircraft passes for an F-15E. This program follows current DoD guidance for pavement design (UFC 2001). For rigid pavement design, the software utilizes a pavement response model based on Westergaard's plate theory that calculates edge stresses under design aircraft. These calculated edge stresses are related to the concrete flexural strength and repetitions of traffic through field fatigue curves based on full-scale accelerated traffic tests of aircraft loads. Based on various inputs, the software can calculate the required PCC thickness or determine the number of allowable passes a given pavement thickness can support under a particular aircraft.

Figure 34. PSeven software.



Inputs required to complete the analyses for each series of repairs include

- Aircraft type (F-15E) and, if computing thickness, number of passes,
- Aircraft gross weight, lb,
- Traffic area (A, B, C, D),
- Wander width, in. (70 in.),
- Failure criteria,
- Modulus of subgrade reaction, lb/in.^{3},
- PCC Poisson's ratio,
- PCC flexural strength, psi,
- PCC modulus of elasticity, psi,
- Percent steel, % (for reinforced pavements only),
- Load transfer, % (DoD assumption is 25%), and
- Base strength, CBR %.

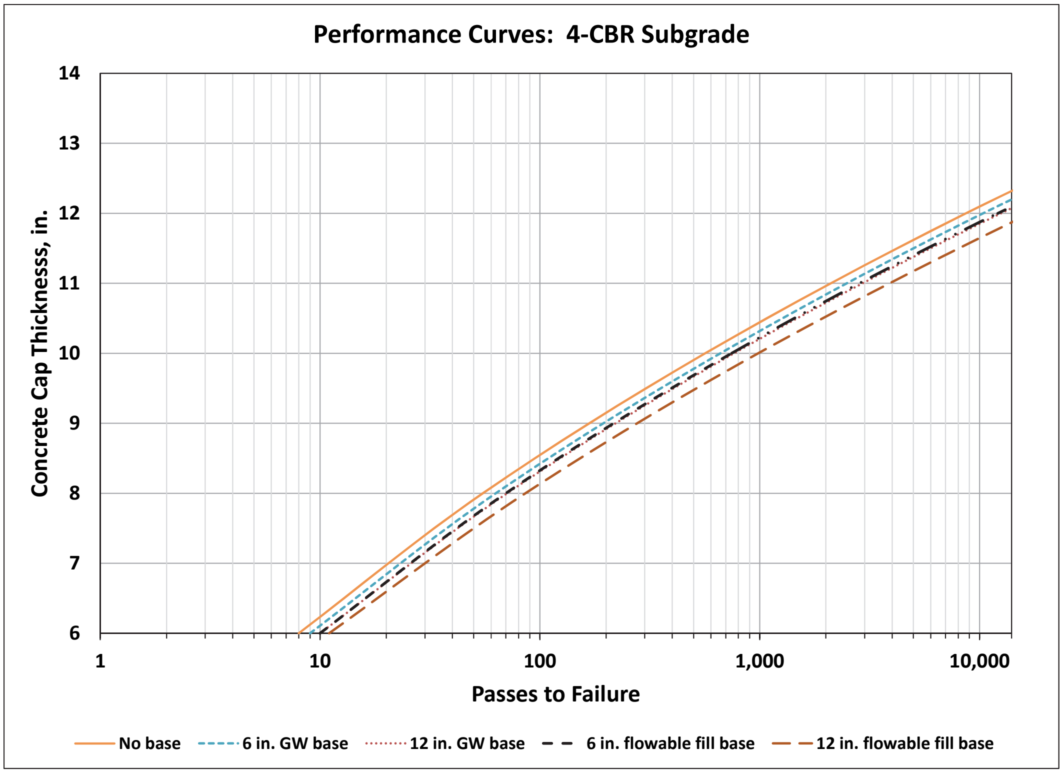
For this investigation, F-15E aircraft traffic with a gross load of 81,000 lb was used for analysis. Type A traffic area (channelized traffic receiving the full design weight of aircraft) and the shattered slab failure criterion was used for analysis. Shattered slab failure is defined as a concrete slab broken into four or more pieces, when 50 percent of the slabs are cracked into approximately four pieces. Other failure criteria include first crack, defined as the occurrence of the first or initial crack appearing on the slab surface when 50 percent of the slabs are cracked into two or three pieces, or complete failure, defined as a concrete slab broken into 25 to 30 pieces or 50 percent or more of the slabs broken.

Subgrade and base strengths were based on target CBR values. Poisson's ratio was based on average laboratory results completed previously for Rapid Set Concrete Mix® (values ranged between 0.18 and 0.22). Flexural strengths of 600 psi were based on laboratory results presented in Chapter 2. Modulus of subgrade reaction values, k (in lb/in.^{3}), were determined from the subgrade strength of 4 CBR, using the equation currently used in DoD pavement design software PCASE to convert DCP CBR estimates for soil CBR < 20:

$$k = -11.25 + 2.19*CBR + 60.23*CBR^{0.5}$$

The performance curves for the various pavement structures on a 4-CBR subgrade are presented in Figure 35. These curves take into account all five series of repairs' structures (no base, 6-in.-thick weak base, 6-in.-thick strong base, 12-in.-thick weak base, and 12-in.-thick strong base).

Figure 35. Predicted repair performance for a 4-CBR subgrade (PSeven).



5.2 Field performance

The results of the traffic tests indicate that increasing the Rapid Set Concrete Mix® cap thickness results in increasing pass levels with the F-15E aircraft, as expected. All series of repairs were able to support more than 100 passes of F-15E traffic without structural failure, as predicted by current design criteria. Table 11 shows the results of the field performance results for each of the 21 repairs as well as the theoretical results.

Trafficking of the Series 1 repairs showed that Rapid Set Concrete Mix® can be used without a base course layer if needed. Furthermore, a 6-in.-thick cap over a 4-CBR silt subgrade exceeds the expedient repair criterion of 100 passes by a factor of 5. These data show that repairs can be completed when rapid-setting concrete capping material and/or base backfill material is scarce, while still providing a minimum number of passes as long as the underlying subgrade material is uniform and compacted.

Table 11. Comparison of theoretical and actual passes to failure.

Series No.	Repair No.	Cap Thickness (in.)	Base Material	Base Thickness (in.)	Theoretical Passes to Failure (PSeven)	Actual Passes to Failure
1	1	6	none	----	8	560
	2	8	none	----	55	1,750
	3	10	none	----	565	3,000
	4-1[a]	12	none	----	8,677	3,000
	4-2	12	none	----	8,677	9,000
	5-1[a]	14	none	----	200,427	2,500
	5-2	14	none	----	200,427	10,000+
2	6	6	GW	6	9	1,290
	7-1[b]	8	GW	6	63	2,500
	7-2	8	GW	6	63	3,500
	8	10	GW	6	663	10,000+
3	9	6	flow fill	6	10	3,900
	10-1[c]	8	flow fill	6	70	10,000+
	10-2	8	flow fill	6	70	10,000+
	11	10	flow fill	6	745	10,000+
4	12	6	flow fill	12	11	10,000+
	13	8	flow fill	12	86	10,000+
	14	10	flow fill	12	985	10,000+
5	15	6	GW	12	10	1,508
	16	8	GW	12	71	8,000
	17	10	GW	12	765	8,500

[a] Repair repeated due to wet subgrade conditions noted after failure

[b] Repair repeated due to early failure

[c] Repair repeated due to low-severity shattered slab occurring after 560 passes

Surprisingly, the repair constructed with 10 in. of the rapid-setting concrete cap over 6 in. of a crushed limestone base (Repair 8) outperformed the repair constructed with 10 in. of the rapid-setting concrete cap over 12 in. of a crushed limestone base (Repair 17) by 1,500 to 2,000 passes. Both base courses had similar CBR strengths and density measurements.

Repair 15, with a 6-in.-thick cap and 12-in.-thick limestone base, failed at approximately the same number of passes as Repair 6; Repair 6 also had a 6-in.-thick concrete cap surface but only 6 in. of the crushed limestone base. This failure was likely due to the rapid-setting concrete's segregating

during placement, as determined in post-test forensics. Core samples showed that the top 2 in. of Repair 15's cap did not contain any coarse aggregate (Figure 36). The Rapid Set Concrete Mix® segregated during construction. It is likely Repair 15 would have lasted several hundred more passes without segregation at the top of the repair.

Figure 36. Repair 15 – aggregate segregation of the Rapid Set Concrete Mix® cap.

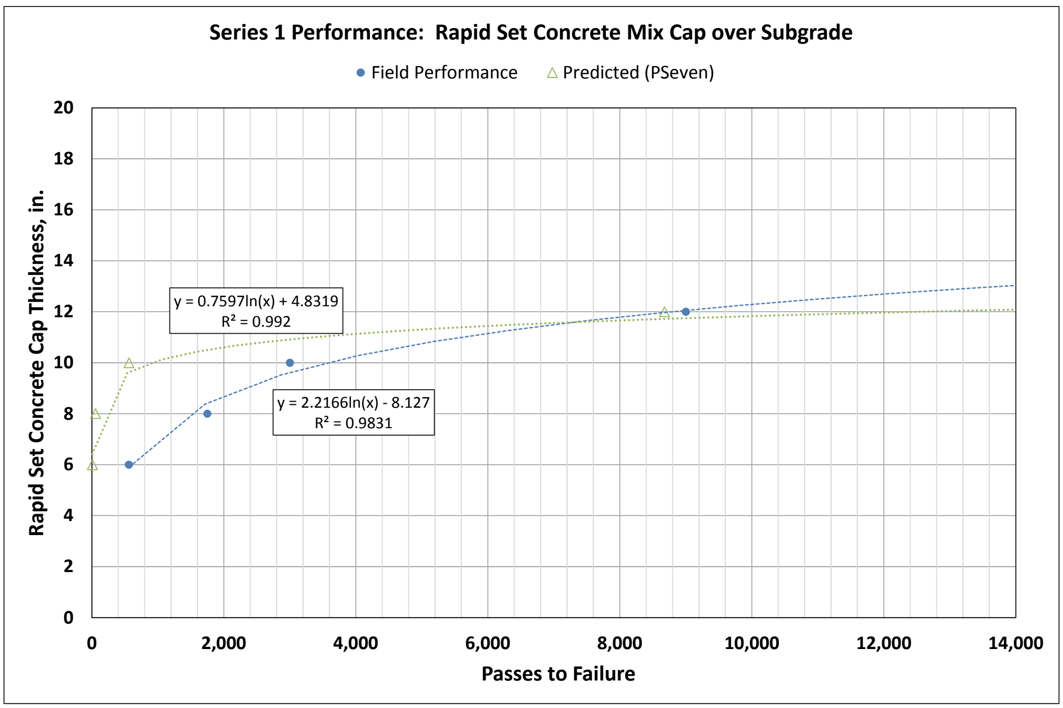
Repairs with the 100-CBR flowable fill base outperformed the repairs constructed with no base and those constructed with a crushed limestone base. With an 8-in.-thick rapid-setting concrete cap and at least 6 in. of a flowable fill base layer, repairs withstood 10,000 passes, making them permanent repairs.

5.3 Performance curves

Performance curves were created using the data from the Series 1 and Series 5 repairs. Performance curves could not be developed for Series 2, 3, and 4 repairs because those repairs did not fail after the application of 10,000 passes or only two failure data points within the series were achieved.

Figure 37 and 38 present the theoretical and performance curves for the Series 1 and 5 repairs, respectively. The curves for both series of tests show that the PSeven linear elastic analysis software under-predicts the field performance of Rapid Set Concrete Mix®, especially with Series 5. The coefficient of determination, or R^2, for the Series 1 data was much higher than the R^2 for the Series 5 data, indicating a better performance prediction for Series 1. The lower R^2 value for the Series 5 performance curve was not surprising due to the segregation near the surface of the Rapid Set Concrete Mix® cap for Repair 15 and the early failure of Repair 17. The Series 5 repairs, particularly Repairs 15 and 17, should be repeated to validate the unanticipated data.

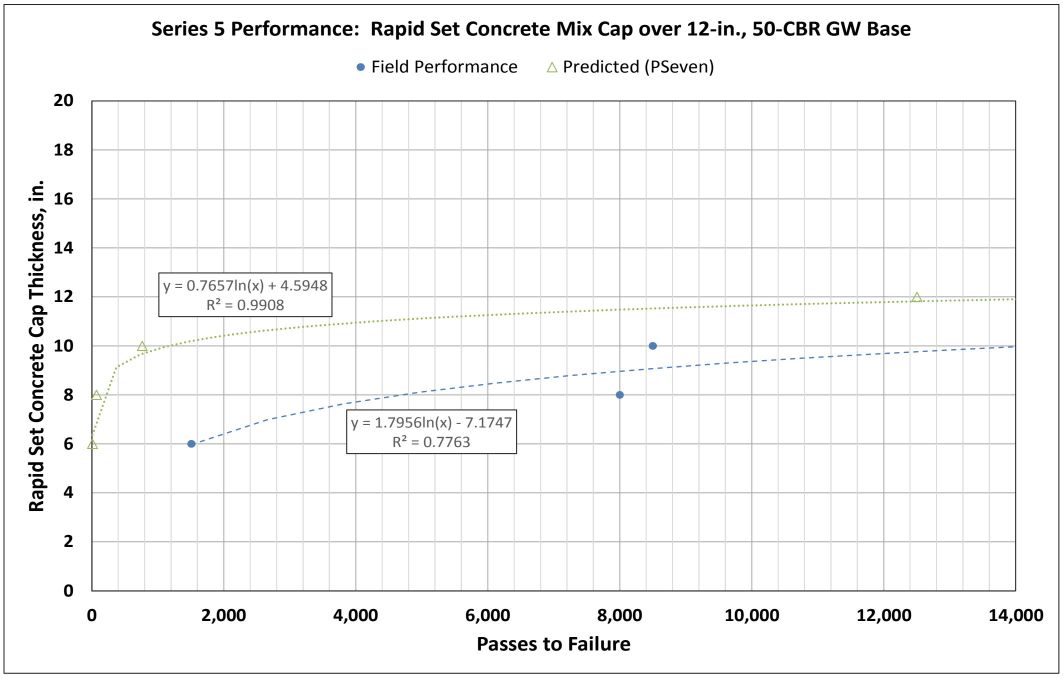
Figure 37. Series 1 field performance and predicted Rapid Set Concrete Mix® Curves.



5.4 Comparison of theoretical and field performance

The results shown in Table 11 indicate that the theoretical performance curves shown in Figure 35 underpredict the field performance of all repair series of tests. This would be expected, as design procedures are generally conservative. The mode of failure (spalling versus shattered slab) was also different.

Figure 38. Series 5 field performance and predicted Rapid Set Concrete Mix® Curves.



The theoretical passes to failure increased by approximately one order of magnitude for every 2-in. increase in thickness of concrete surface between 6 and 10 in. thick, which was not the case for the field measurements. For a 6-in.-thick Rapid Set Concrete Mix® cap over any of the backfill conditions examined in this project, current pavement design theory indicates only approximately 10 passes can be achieved prior to structural failure (shattered slab). Field performance shows that even with a 6-in.-thick cap over a weak subgrade (Repair 1), several hundred passes can be applied prior to functional failure of the repair caps (spalling). The theoretical prediction for the 8-in.-thick rapid-setting cap over any of the backfill conditions evaluated in this project was approximately 70 passes of the F-15E aircraft, while the theoretical prediction for the 10-in.-thick caps was approximately 700 passes. The field performance for the 8-in.-thick caps was at least 25 times higher than the theoretical prediction, and the field performance of the 10-in.-thick caps was at least 3 times higher. The theoretical prediction for the 12-in.-thick cap over a weak subgrade (Repair 4-2), however, matched the field performance, while the 14-in.-thick cap of Repair 5 -2 was underpredicted.

The numerical analysis indicates that the backfill material strength and thickness does not influence the failure results as much as the thickness of the rapid-setting cap. However, the field results indicate, for the most part, that failure is influenced by all three variables: the Rapid Set Concrete Mix® thickness, backfill strength, and backfill thickness.

6 Conclusions and Recommendations

Twenty-one repairs, separated into five series of tests, were repaired with varying thicknesses of Rapid Set Concrete Mix® and base materials. The repairs were trafficked with a single-wheel F-15E load cart with a wheel load of 35,235 lb and a 325-psi tire pressure. Traffic was applied until either failure occurred or 10,000 passes had been applied. Conclusions and recommendations determined from the test results are presented in the following sections.

6.1 Conclusions

- Predicted performance using PSeven linear elastic analysis software underpredicted the field performance of the Rapid Set Concrete Mix® repairs. This is logical, as design methods are typically conservative and the mode of failure (spalling versus shattered slab) was different in the field.
- The theoretical predictions were influenced mostly by the concrete surface thickness rather than the backfill material strength and thickness.
- Repair failure was primarily functional failure rather than structural failure due to high-severity joint spalling along the trafficked repair joints. No settlement or faulting of the repairs occurred.
- A minimum 6-in.-thick Rapid Set Concrete Mix® cap over a weak (4 CBR) subgrade supported more than 500 passes of the F-15E load cart; this exceeded theoretical predictions by a factor of 70.
- A minimum 14-in.-thick Rapid Set Concrete Mix® cap is needed to support at least 10,000 passes of the F-15E aircraft when placed over a weak (4 CBR) subgrade with no base layer.
- A minimum 10-in.-thick Rapid Set Concrete Mix® cap is needed to support at least 10,000 passes of the F-15E aircraft when placed over 6 to 12 in. of a medium-strength (50 CBR) crushed stone base.
- A minimum 8-in.-thick Rapid Set Concrete Mix® cap is needed to support 10,000 or more passes when placed over a 6-in.-thick high-strength (100 CBR) flowable fill base.
- The use of a 12-in.-thick flowable fill base decreases the required Rapid Set Concrete Mix® minimum cap thickness to support 10,000 or more passes of an F-15E aircraft from 8 in. to 6 in.

- For F-15E traffic, 8 in. of CTS Rapid Set Concrete Mix® placed over 12 in. of wet-placed flowable fill should provide adequate structural performance for the life of the repair. For multiple-wheel heavy aircraft, the foundation support becomes more important, and the required depth of flowable fill is likely higher.

6.2 Recommendations

It is recommended that the Series 5 tests, consisting of Rapid Set Concrete Mix® over 12 in. of GW base material, be repeated. The forensics of the 6-in.-thick rapid-setting concrete cap showed segregation at the top 2 in. of the repair. Also, the 8- and 10-in.-thick rapid-setting concrete capped repairs failed at essentially the same number of passes. The 10-in.-thick repair with the 12-in.-thick GW base did not perform as well as the 10-in.-thick repair with the 6-in.-thick GW base. The repairs were unable to be repeated during this research time frame due to time, manpower, and monetary constraints.

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Appendix A: Repair Notes and Data

Table A1. Series 1 distresses noted during trafficking.

Repair	Description	Passes	Visual Observation	FOD Potential
1	6-in. cap/ subgrade	0	Shrinkage cracks covered over 30% of the surface.	Low
		112	Low-severity joint spall was noticed on west repair edge. The cracks were hairline with no FOD.	Low
		224	The spall on the west repair edge lengthened and widened in places. Small pieces of FOD <0.125 in. were noticed. When swept, the largest area with removed FOD was 10 in. long and 1.5 in. wide. In addition, hairline cracks were noticed on the east repair edge.	Moderate
		336	The FOD production on the west repair edge continued with produced FOD <0.5 in. Popping noises were heard after every pass over the east repair edge. No FOD was noticed on the east repair edge; however, the cracks lengthened.	Moderate
		448	The FOD production on the west repair edge continued with FOD 0.5 to 1 in. The total spalled region on the west edge was 43 in. long, 4.5 in. wide, and 1.25 in. deep. There were no noted changes on the east repair edge. Popping noises were noted during trafficking when the east edge was crossed.	Moderate
		560	The FOD production on the west repair edge increased with small FOD <0.5 in. produced during trafficking. The spall was 52 in. long, 12 in. wide, and 2.5 in. deep. The east repair edge produced small FOD <0.5 in. during trafficking, resulting in a spalled area 7 in. long, 6.5 in. wide, and 1.25 in. deep. The repair was considered a fail due to the west edge spall.	High
2	8-in. cap/subgrade	0	No distresses were noted.	Low
		112	A hairline crack approximately 3 ft long was noticed on the west edge.	Low
		224	Small FOD <0.125 in. was produced on west edge.	Low
		336	A spall approximately 8.5 ft long with FOD <0.125 in. was noted on the east edge. More hairline cracking with spall length totaling 8 ft. and FOD <0.125 in. was noted on west edge. Small corner breaks were noted on southeast and southwest corners near saw overcuts.	Low
		448	Minor FOD <0.25 in. was noted on west and east edges. Spalling was progressing, but spalled areas were <2.0 in. wide.	Low
		560	No change was noted.	Low
		672	The east and west edge spalls were producing 0.5-in. FOD.	Moderate
		784	The west edge spall was 82 in. long, 3.5 in. wide, and 0.75 in. deep. The east edge spall was 8.5 ft long, 4.5 in. wide, and 1 in. deep.	Moderate
		896	The west edge spall was 83 in. long, 3.5 in. wide, and 0.75 in. deep. FOD size for this spall was 0.5 in. The east edge spall was 8.5 ft long, 5 in. wide, and 1.25 in. deep. FOD size for this spall was 0.75 in.	Moderate
		1,008	The west edge spall increased to 4 in. wide and 1.5 in. deep. The FOD on west edge had a maximum size of 1 in. The east edge spall increased to 5 in. wide and was 1.75 in. deep.	Moderate

Repair	Description	Passes	Visual Observation	FOD Potential
		1,500	A crack which did not extend to the edges was noted across the center of the repair. The west edge spall increased in width to 4.5 in. and a depth of 1.5 in. with 2.0-in. FOD. The east edge spall increased in width to 5.5 in. and had a depth of 1.75 in. Maximum FOD size for the east edge was 3 in.	High
		1,750	The east edge spalling increased to a width of 6.5 in. a depth of 2 in., and a length of 8.5 ft. The west edge spall did not increase in severity. Several hairline cracks formed, creating a shattered slab. At this time, the repair was considered failed due to the east edge spall.	High
3	10-in. cap/subgrade	0	Prior to trafficking, distresses were noted on the west edge of the repair where material had not been distributed completely to the pavement edge. These distresses were recorded as spalls and were approximately 2.0 in. long and approximately 0.5 in. wide. A few shrinkage cracks were noted prior to trafficking.	Low
		112	No change was noted.	Low
		250	A crack was noticed in the northeast corner of the repair where overcutting of the repair boundaries occurred. Cracks were noted in all corners of the repair near the overcuts. A spall was noted on the south edge of the repair that was 24 in. long, 2 in. wide, and 0.5 in. deep. FOD produced was <0.375 in.	Low
		560	The spall on the south edge lengthened to approximately 8 ft. FOD produced was <0.375 in.	Low
		1,008	Spalling continued on north and south edges with FOD <0.5 in. Maximum spalled area width was 5.5 in. on the north edge. The south edge spall maximum width was 5 in.	Low
		1,500	The spall on the north edge was 81in. long, 4.5 in. wide, and 0.5 in. deep. 0.5-in. FOD was produced. The south edge spall was 8.5 ft long, 5 in. wide, and 1 in. deep.	Low
		2,000	The north edge spall dimensions increased to 8.5 ft long, 6 in. wide, and 0.5 in. deep. The south edge spall was 8.5 ft long, 5 in. wide, and 1 in. deep. Some cracking was noted on the west edge.	Low
		2,500	Smaller FOD was generated in the spalls with size of 0.5 to 0.75 in. The north edge spall was 8.5 ft long, 6 in. wide, and 1.25 in. deep. The south edge spall was 8.5 ft long, 5 in. wide, and 1.25 in. deep. No cracks were noted in the center of the repair.	Moderate
		3,000	FOD up to 2 in. was generated on the north and south edges. The north edge spall was 8.5 ft long, 6 in. wide, and 2.5 in. deep. The south edge spall was 8.5 ft long, 6 in. wide, and 1.25 in. deep. No cracks were noted in the center of the repair. At this time, the repair was considered failed due to the north edge spall.	High
4-1	12-in. cap/subgrade	0	A small void was noted in the northeast corner of the repair due to finishing.	Low
		112	No change was noted.	Low
		250	Cracks were noted in the northeast and northwest corners.	Low
		560	A joint spall that was approximately 5 ft long and 1 in. wide with FOD <0.375 in. was noted on the north edge. Another joint spall that was approximately 8 ft long and 1 in. wide with FOD <0.375 in. was noted on the south edge of the repair. A joint spall that was approximately 3 ft long with FOD less than 0.375 in. was also noted on the west joint in the center.	Low

Repair	Description	Passes	Visual Observation	FOD Potential
		1,008	The spall on north edge was 8.5 ft long and was producing 0.5-in. FOD. The south edge spall was producing 1-in. FOD and had a maximum spalled width of 2 in.	Low
		1,500	The spall on north edge was 8.5 ft long, 5 in. wide, and 0.31 in. deep. The spall was producing 0.5-in. FOD. The south edge spall was 8.5 ft long, 3.75 in. wide, and 0.75 in. deep. The south edge was producing 2-in. FOD. Repair was rocking under traffic.	Moderate
		2,000	The spall on the north edge was 8.5 ft long, 5 in. wide, and 1 in. deep. The south edge spall was 8.5 ft long, 3.75 in. wide, and 1 in. deep. The west edge spall was 8.5 in. long.	Moderate
		2,500	FOD was generated on all edges. The maximum size measured was 2 in. The north edge spall was 8.5 ft long, 4 in. wide, and 1.25 in. deep. The south edge was 8.5 ft long, 3 in. wide, and 1.25 in. deep. No cracks were noted in the center of the repair.	Moderate
		3,000	FOD was generated on all edges. The maximum size FOD was 2 in. The north edge spall was 8.5 ft long, 4 in. wide, and 2 in. deep. The south edge spall was 8.5 ft long, 3.5 in. wide, and 2 in. deep. Corner spalls were generated on all four corners producing FOD. The repair was considered failed due to spalling on north and south edges.	High
4-2	12-in. cap/subgrade	0	No distresses were noted; however, the west edge finish was rough.	Low
		112	No change was noted.	Low
		448	No change was noted.	Low
		560	No change was noted.	Low
		1,008	A hairline crack approximately 18 in. long was noted near the west edge. A corner spall was forming on the southwest corner with no FOD. Spalling was noted along the entire south edge producing 0.25-in. FOD.	Low
		1,500	The hairline crack along the west edge measured 37 in. long. The corner spall on the southwest corner was producing small FOD <0.25 in. The south edge spall was producing 0.38-in. FOD and was approximately 1 in. wide. An 83-in.-long spall with a maximum depth of 0.75 in. and 0.5-in. FOD was noticed on the east edge.	Moderate
		2,000	The west edge crack formed into a spall that was 56 in. long and 1 in. wide and had a maximum depth of 0.25 in. The south edge spall was 87 in. long and 2 in. wide and had a maximum depth of 0.5 in. This spall was producing 1.25-in. FOD. The east edge spall was 84 in. long, 2.5 in. wide, and 0.75 in. deep with a maximum FOD size of 0.5 in.	Moderate
		2,500	The west edge spall was 86 in. long, 1.75 in. wide, and 0.5 in. deep producing 0.75-in. FOD. The south edge spall was 96 in. long, 2 in. wide, and 1 in. deep, producing minimal FOD. The east edge spall was 98 in. long, 2.5 in. wide, and 0.75 in. deep, producing 0.75-in. FOD.	Moderate
		3,000	The west edge spall was producing 0.5-in. FOD. The south edge spall was producing 1-in. FOD in a couple of places. The east edge spall was producing 0.38-in. FOD. Overall, the repair condition had not changed significantly.	Moderate

Repair	Description	Passes	Visual Observation	FOD Potential
		5,000	The west edge spall was producing 0.5-in. FOD and was 86 in. long, 2.25 in. wide, and 0.5 in. deep. The south edge spall was producing 1-in. FOD and was 103 in. long, 3.5 in. wide, and 1 in. deep. The east edge spall was producing 1-in. FOD and was 98 in. long, 4.5 in. wide, and 1.5 in. deep.	Moderate
		7,500	The west edge spall was producing 0.75-in. FOD with a maximum width of 1.5-in. FOD. The spall was 86 in. long, 3.75 in. wide, and 1 in. deep. The south edge was producing a small amount of 1-in. FOD and was 103 in. long, 4 in. wide, and 1.25 in. deep. The east edge spall was producing 2-in. FOD and was 98 in. long, 6.75 in. wide, and 2 in. deep.	Moderate
		9,000	The west edge spall was producing 0.5-in. FOD with a maximum FOD size of 1 in. The west edge spall was 86 in. long, 6.0 in. wide, and 1.125 in. deep. The south edge spall was 103 in. long and generated 1.25-in. FOD. The south edge spall width was 4 in. and had a maximum depth of 1.25 in. The east edge spall was 98 in. long, 6.75 in. wide, and 2 in. deep. This spall was producing <0.25-in. FOD. At this time, traffic was discontinued, and the repair was not considered failed.	Moderate
5-1	14-in. cap/subgrade	0	No distresses were noted.	Low
		112	Hairline crack was noted near the southeast corner of the repair.	Low
		250	Hairline cracks were noted on the northwest, southwest, and southeast corners of the repair.	Low
		560	A spall was noted on the north edge of the repair that was approximately 2 ft long. Hairline cracks, approximately 1 ft long within 0.5 in. of the edge of the repair, were noted on the west edge. A spall that was approximately 5 ft long and 0.5 in. wide, producing a couple of pieces of 0.5-in. FOD, was noted on the south edge of the repair.	Low
		1,008	Spalling continued on all four edges.	Low
		1,500	The north edge spall was 8.5 in. long, 5.5 in. wide, and 1 in. deep. The north edge was producing 1-in. FOD. The south edge was 82 in. long, 4 in. wide, and 1.25 in. deep. The south edge was producing 0.5-to 1-in. FOD. The repair rocked under traffic.	Moderate
		2,000	The north edge spall increased to 6 in. wide and was 1.5 in. deep. The south edge spall was 84 in. long, 4.5 in. wide, and 1.75 in. deep. The east and west edges were also spalling.	Moderate
		2,500	The north and west edges were spalling; however, very few pieces of FOD were generated on the south edge. A high-severity corner spall was noted on the southeast corner. The spall on the north edge was 8.5 ft long, 5.25 in. wide, and 2.75 in. deep. The maximum FOD size was 3 in. The south edge was 84 in. long, 4.5 in. wide, and 1.75 in. deep. The maximum FOD size was 2 in. The repair was considered failed due to the spall on the north edge.	High
5-2	14-in. cap/subgrade	0	No distresses were noted; however, the north and west edges had rough finishes.	Low
		112	No changes were noted.	Low
		448	A 2-in.-long hairline crack approximately 2 ft from the west edge was noted.	Low
		560	No changes were noted.	Low

Repair	Description	Passes	Visual Observation	FOD Potential
		1,008	The hairline crack on the west edge formed into a joint spall with no FOD. A hairline crack was noted near the southwest corner. The entire length of the east edge was spalling, and hairline cracks were noticed on the southeast and northeast corners.	Low
		1,500	The west edge spall was 47 in. long and was producing <0.38-in. FOD. A crack that was 93 in. long with no FOD was noted parallel to the south edge.	Low
		2,000	The west edge spall was 67 in. long with no FOD. The north edge had a few pieces of 0.75-in. FOD. The east edge had a 91-in.-long spall with 2-in. FOD near the northeast edge. It was 0.5 in. wide and 0.5 in. deep. The south edge crack was still not producing FOD.	Moderate
		2,500	The west edge spall did not change in length, but cracking was noted. A crack was also noted along the north edge. The south edge spall was 91 in. long but was not widening or producing FOD. The east edge spall was 93 in. long, 2.5 in. wide, and 1 in. deep, producing 0.25-to 1.5-in. FOD near the northeast edge.	Moderate
		3,000	The west edge spall was producing 0.25-in. FOD. No significant change was noted for the repair.	Moderate
		5,000	The west edge spall was producing 0.5-in. FOD. The west edge spall was 80 in. long, 2 in. wide, and 0.25 in. deep. A small amount of 0.25-in. FOD was produced on the north edge. The entire length of the east edge was spalled and was producing some 0.5-in. FOD. The east edge spall was 2.5 in. wide and 0.75 in. deep. The entire length of the south edge was spalled with some 0.5-to 1-in. FOD. The south edge spall was 1 in. wide and 0.25 in. deep.	Moderate
		7,500	The west edge spall was 80 in. long, 2.25 in. wide, and 1 in. deep. The north edge had 1.5-in.-cracked pieces that were noted. The south edge spall included the entire length, was 2.75 in. wide, and was 0.75 in. deep. The east edge spall was 90 in. long, 3 in. wide, and 1 in. deep and was producing 0.5-in. FOD.	Moderate
		10,000	Some <0.5-in. FOD was noticed on the west edge. The spall was 80 in. long, 2.25 in. wide, and 1.125 in. deep. No real change was noted on the north or south edges of the repair. The east edge spall was 90 in. long, 3 in. wide, and 1.125 in. deep. FOD produced was <0.5 in. At this time, traffic was discontinued, and the repair was not considered failed.	Moderate

Table A2. Series 2 distresses noted during trafficking.

Repair	Description	Passes	Visual Observation	FOD Potential
6	6-in. cap/6-in. limestone base	0	No distresses were noticed prior to traffic.	Low
		112	Hairline crack forming a spall was noticed on east repair edge. Small pieces of 0.25-in. FOD were noticed. The area with FOD was 5 in. long and 0.5 in. wide.	Low
		560	Cracking on east edge was 48 in. long. A crack that was 6 in. long and 0.25 in. deep was noticed on the north edge. Hairline cracks were noticed on the west and north edges.	Moderate
		1,008	A spall that was approximately 65 in. long, 6 in. wide, and 0.5 in. deep with FOD less than 1.5 in. was noticed on the east edge. The west edge had a spall that was 56 in. long, 7 in. wide, and produced FOD less than 0.5 in. No changes were noted for the north or south edges.	Moderate
		1,300	The west edge spall increased to 58 in. long and 8 in. wide. The spall on the east edge was 59 in. long, 7 in. wide, and 0.75 in. deep. Popping noises were noted when trafficking crossed the east edge. The repair was considered failed due to east edge spalls presenting a tire hazard.	High
7-1	8-in. cap/6-in. limestone base	0	No distresses noticed prior to traffic.	Low
		112	A hairline crack approximately 19 in. long was noticed on the east edge.	Low
		560	A 13-in.-long spall was noted on the east edge at the location of a spall in the parent slab. The FOD produced was less than 0.5 in. Hairline cracking was noted on the other edges and on the west side of the repair.	Low
		1,008	The spall on the east edge was 30 in. long, 3 in. wide, and 0.5 in. deep and was producing 0.75-in. FOD. The west edge spall was 28 in. long and 3.5 in. wide. In addition, a longitudinal crack was noted across the entire repair.	Moderate
		1,500	The spall on the east edge was 38 in. long, 4 in. wide, and 0.5 in. deep and was producing 1-in. FOD. Most of the spalling on the east edge was due to the spalled parent slab edges. The west edge spall was 32 in. long and 2.5 in. wide.	Moderate
		2,000	The east edge spall increased to 41 in. long and 1.75 in. deep. The west edge spall was producing 0.5-in. FOD and had a maximum spall length of 36 in.	Moderate
		2,500	The east spall was producing 1.5-in. FOD and had maximum dimensions of 71 in. long, 6 in. wide and 2 in. deep. At this time, the repair was considered failed due to the spall on the east edge.	High
7-2	8-in. cap/6-in. limestone base	0	A few shrinkage cracks (approximately 20 in. long) formed perpendicular to all four joints.	Low
		112	All four corners had cracks. A few more shrinkage cracks were forming, mainly from the north and south edges; some were 0.125 in. wide. The north edge looked good. The majority of the south edge had low-severity cracks. The north center area of the west edge was broken up with 0.5-in. FOD; the spall along the west edge was approximately 30 in. long, 3.5 in. wide, and 0.25 in. deep. The east edge had parallel cracks that were mostly connected.	Low
		560	The spall on the west edge increased in length to cover the entire edge, was 4 in. wide, and was 0.25 in. deep. Some 0.5-in. FOD was	Moderate

Repair	Description	Passes	Visual Observation	FOD Potential
			breaking out on the north end. The east edge was spalled along its entire edge with minimal FOD (0.25 in.); the spall was not breaking out much. The east edge spall had a maximum width of 4 in. and was 0.375 in. deep.	
		770	The entire length of the west edge was spalled. The 30-in.-long center spall was high-severity with a large amount of 0.5-in. FOD. The maximum spall width and depth was 3 and 0.5 in., respectively. The east edge had low-severity spalling spanning the entire joint. The maximum FOD size was 0.25 in., the maximum spall width was 4 in., and the maximum spall depth was 0.125 in.	High
		1,008	The high-severity spall along the west edge was developing, and the maximum width and depth were 3 in. and 0.875 in., respectively. The average FOD size was 0.5 in., and the maximum size was 1.125 in. The east edge did not have much FOD. The spall was developing into medium-severity with a maximum width and depth of 5 and 0.125 in., respectively.	High
		2,000	The west joint contained FOD along the entire edge with a maximum size of 1.5 in. The spall on the west joint was 3.75 in. wide and 1.25 in. deep. The entire edge of the east joint was spalled with an 8 in. width and a 1.125 in. depth. There was a large amount of 1-in. FOD in the north-center area with a maximum FOD size of 1.5 in.	High
		3,000	The west edge with a 3.75 in. width and a 1.5 in. depth did not have a considerable change. The spall along the east joint was broken up more. The average and maximum size FOD was 1 in. The spall width and depth were 8 and 1.625 in., respectively.	High
		3,500	The spall along the west joint had not produced considerable FOD. The maximum spall width was 3.5 in., and the maximum spall depth was 1.75 in. The east edge was a tire hazard, so the repair was failed. The repair also recently began making popping noises as the traffic passed over it. The spall length was across the entire joint, the maximum spall width was 8 in., and the maximum spall depth was 1.875 in. The length of the opened spall was 42 in. Many cracks formed off of the open spall. The average FOD size was 0.625 in., and the maximum FOD size was 2.5 in.	High
8	10-in. cap/6-in. limestone base	0	A small spall noticed on the north edge was approximately 8.0 in.	Low
		112	No changes were noted.	Low
		560	Hairline cracking approximately 4 ft long on the north and east edge was noted. Cracking was noted along the entire south edge. There was no FOD. The west repair edge was spalling with a length of approximately 6 in.	Low
		1,008	A low-severity crack was noted across the entire repair. The west edge spalling increased to 30 in. long and 3 in. wide. More hairline cracks were noted on the east edge with a spall length totaling 36 in. The FOD noted on the east edge was less than 0.125 in.	Low
		1,500	The spall on the west side was 35 in. long. The east edge spall was 56 in. long, 4 in. wide, and 0.125 in. deep. The east edge spall was producing 0.5-in. FOD.	Low
		2,000	The west edge spalling was 40 in. long and 3.25 in. wide. The west edge spall was producing 0.5-in. FOD. The east spall edge was producing <0.75-in. FOD and had a maximum spalled length of 60 in.	Moderate
		2,500	The east edge spall dimensions increased to 72 in. long and 0.5 in. deep. The east edge was producing 1-in. FOD.	Moderate
		3,000	The east edge had a maximum width of 4.5 in. The crack on the south edge was 56 in. long. The crack at the north edge was 57 in. long.	Moderate

Repair	Description	Passes	Visual Observation	FOD Potential
		3,500	FOD that was <0.625 in. was noticed on the east edge. The spall was 80 in. long and 1 in. deep. The west edge spall was 60 in. long and 0.75 in. deep. No notable changes were noted on the north or south edges of the repair.	Moderate
		4,000	The spall on the west edge was 70 in. long and 3 in. wide and was producing <0.75-in. FOD. The east spall was producing 1-in. FOD with a maximum spall width of 5 in.	Moderate
		4,500	The west edge spall was 72 in. long and 1 in. deep. The east edge spall had a maximum length of 81 in. The crack on the north side was 90 in. long. The south crack had a maximum length of 87 in.	Moderate
		5,000	The east edge spall was 93 in. long and 1.5 in. deep. The maximum FOD size was 2 in. The spall of the west edge was 75 in. long, 3.5 in. wide, and 1.25 in. deep. The cracks at the north and south edge were 102 in. long.	Moderate
		5,500	The east edge spall had a maximum length of 93 in. The spall of the west edge was 80 in. long. A 44-in.-long transversal crack was noticed at the center of the repair.	Moderate
		6,000	The east edge spall did not change in length, but it had a maximum depth of 1.75 in. The transverse hairline crack was 48 in. long.	Moderate
		7,000	The east edge spall was 5.5 in. wide and 1.63 in. deep. Some FOD was noticed on the east edge spall. No notable changes were present for the west, north, or south edges of the repair.	Moderate
		8,000	The east edge spall was 1.875 in. deep. Some FOD that was <0.5 in. was noticed on the west edge.	Moderate
		10,000	The east edge spall was 93 in. long, 6 in. wide, and 1.875 in. deep. The east edge spall was producing 0.375-in. FOD. The west edge spall was 8 in. long, 4 in. wide, and 1.25 in. deep. At this time, traffic was discontinued, and the repair was not considered failed.	Moderate

Table A3. Series 3 distresses noted during trafficking.

Repair	Description	Passes	Visual Observation	FOD Potential
9	6-in. cap/6-in. flowable fill base	0	Several shrinkage cracks across approximately 25% of the repair surface were noted prior to traffic.	Low
		112	No changes were noted.	Low
		560	A spall on the east edge was noted that was 30 in. long with no FOD. A spall on the west edge was also noted that was 60 in. long and was producing 0.125-in. FOD.	Low
		1,008	The spall on the east edge had additional cracks form, but no new FOD. The west edge spall was 48 in. long, 2.5 in. wide, and 0.5 in. deep. The maximum FOD was 0.5 in. wide.	Low
		1,500	The east edge spall was 30 in. long and 1 in. wide and was producing 0.5-in. FOD. The west edge spall was 54 in. long, 2.75 in. wide, and 0.94 in. deep. The maximum FOD size was 0.5 in.	Moderate
		2,000	The north edge developed a small crack that was 18 in. long, but it was producing no FOD. The east edge spall was 60 in. long, 2 in. wide, and 0.25 in. deep. The west edge spall was 56 in. long, 4 in. wide, and 1.4 in. deep. The maximum FOD size was 1 in. Popping noises were noted during trafficking along the west edge.	Moderate
		2,500	The east edge spall was 60 in. long, 2 in. wide, and 0.25 in. deep. Maximum FOD size was 0.4 in. The west edge spall was 56 in. long, 4.5 in. wide, and 1.5 in. deep. The maximum FOD size was 0.5 in.	Moderate
		3,000	The east edge was 60 in. long, 2 in. wide, and 0.25 in. deep. The maximum FOD size was 0.25 in. The west edge spall was 62 in. long, 5 in. wide, and 1.9 in. wide. The FOD size was 0.125 to 1.5 in. wide.	Moderate
		3,500	The east edge spall was 65 in. long, 2 in. wide, and 0.25 in. deep. The maximum FOD size was 0.5 in. The west edge spall was 62 in. long, 4 in. wide, and 1.875 in. deep. The maximum FOD size was 0.5 to 1 in.	Moderate
		3,900	The east edge spall was 65 in. long, 2 in. wide, and 0.75 in. deep. The maximum FOD size was 0.375 in. The west edge spall was 62 in. long, 6.5 in. wide, and 2 in. deep. The maximum FOD size was 1 in. Due to the severity of the west edge spall, the repair was considered failed and trafficking was discontinued.	High
10-1	8-in. cap/6-in. flowable fill base	0	Few shrinkage cracks were noted along the east edge of the repair and the southwest corner.	Low
		112	No changes were noted.	Low
		560	A corner break was noted on the southeast edge of the repair. Three shrinkage cracks noted in the center of the repair (running north to south) connected to the corner break from the center crack and to the west edge and resulted in a low-severity shattered slab with no FOD.	Low
		1,008	The shattered slab had not increased in severity, nor was it producing FOD or rocking under traffic. Hairline cracks were noted on the west and east edges; however, no FOD was noticed.	Low
		1,500	A 50-in.-long crack was noted on the east edge of the repair. The cracks causing the shattered slab did not widen or spall.	Low
		2,000	The crack on the east edge of the repair increased in length to 64 in. Another hairline crack, which was 19 in. long, was noted along the west edge of the repair.	Low
		2,500	No changes were noted.	Low

Repair	Description	Passes	Visual Observation	FOD Potential
		3,000	Low-severity cracks from the northeast, southeast, and southwest repair corners extending to the corners of the parent slab were noticed. The center crack extended to approximately 2 ft in length. Hairline cracks along the west edge extended the length of the repair. The east edge crack extended the length of the east edge with approximately 2 ft of spalling. In the spalled area, the width was 1.5 in. with no depth.	Low
		5,000	The west edge cracks progressed to 5.5-in.-long and 3-in.-long spalled areas with a max width of 1 in. and no depth. The east edge spalled area was 30 in. long and 2 in. wide with 0.25- to 0.5-in. FOD.	Low
		6,000	The west edge was producing up to 0.25-in. FOD and was 30 in. long, 2.5 in. wide, and 0.25 in. deep. The east edge spall was 31 in. long, 2 in. wide, and 0.5 in. deep. Neither the shattered slab nor the corner break was progressing in damage. Maximum FOD size was 1 in. on the east edge.	Moderate
		7,000	The east edge spall was 60 in. long, 2 in. wide, and 0.25 in. deep. The spall was producing 0.4- to 0.5-in. FOD. The west edge spall was 49 in. long, 3 in. wide, and 0.25 in. deep and was producing 0.4-in. FOD.	Moderate
		10,000	The east edge spall was 78 in. long, 2 in. wide, and 0.75 in. deep with 0.5-in FOD. The west edge spall was 80 in. long, 3 in. wide, and 0.25 in. deep producing no FOD. No change was noted in the shattered slab or the corner break. The repair had not failed; trafficking was discontinued.	Moderate
10-2	8-in. cap/6-in. flowable fill base	0	Shrinkage cracks covered most of the surface of the repair.	Low
		112	Cracks were noted in the southeast and southwest corners, and a new 25-in.-long crack developed from the center of the west joint.	Low
		560	Some of the preexisting shrinkage cracks widened. The north edge had a 0.125-in.-wide crack along the joint that was breaking up some in the center. The south edge also had a crack; however, it was not as wide; the south edge looked better than the north edge. The west joint had a crack that was about 0.125 in. wide from the north end to the center. A small crack also developed from the center of the west joint to the south end. The east joint had the same cracks as the west joint. All four corners were cracked.	Low
		1,008	No major changes. The west joint had a 27-in.-long and 1.5-in.-wide crack along the center.	Low
		2,000	The west edge looked the same. The east edge had developed some 0.0625-in. FOD in a center 12-in.-long and 3-in.-wide spall. All other cracks were the same.	Moderate
		3,000	The center of the western joint was starting to break up, but no FOD had developed. The spall was 30 in. long and 1.75 in. wide. The eastern joint had not changed much. The spall length was 34 in., and the width was 3 in. A small amount of 0.0625-in. FOD was around the spall.	Moderate
		4,000	No changes were noted.	Moderate
		5,000	The west edge had cracking along the center and north edge with no spalling or FOD. The east edge had cracking from the center to the north end. The center area had a 10-in.long, 1-in.-wide, and 0.125-in.-deep spall with a very small amount of FOD.	Moderate
		6,000	No changes were noted.	Moderate
		7,000	No changes were noted for the west edge. The east edge had two spalls. One spall was 12 in. long, 2.5 in. wide, and 0.125 in. deep. The very small amount of FOD was about 0.0625 in. The second spall was 26.5 in. long and 3. 5 in. wide.	Moderate

Repair	Description	Passes	Visual Observation	FOD Potential
		8,000	No changes were noted.	Moderate
		10,000	The west joint had no spalling; just some cracking. The east joint had cracking along the north end to the center and one crack along the southern end. An 11-in.-long, 1-in.-wide, and 0.125-in.-deep low-severity spall was in the center.	Moderate
11	10-in. cap/6-in. flowable fill base	0	No distresses were noted prior to traffic.	Low
		112	No changes were noted.	Low
		560	A corner break was noted on the southeast corner. On the west edge, a crack was noted that was 24 in. long with no FOD.	Low
		1,008	No changes were noted.	Low
		1,500	No changes were noted.	Low
		2,000	No changes were noted.	Low
		3,000	Parallel edge cracks were noticed on the west and east edges of the repair. Cracks were noticed from the northwest and southeast corners of the repair to the corners of the parent slabs.	Low
		4,000	On the west edge of the repair a spall that was 40 in. long, 0.5 in. wide, and had no depth was noted. FOD <0.5 in. was noticed. The east edge cracks had not progressed.	Low
		5,000	The parallel cracks on the west edge extended the length of the edge. No change was noted in the spalled area on the west edge. The east edge was producing FOD up to 0.5 in.	Low
		6,000	The west edge spall was 40 in. long, 0.5 in. wide, and had no depth. It was producing 0.25-in. FOD. The east edge spall was 46 in. long, 1.5 in. wide, and 0.25 in. deep. No change was noted on the corner break in the southeast corner.	Low
		7,000	Two cracks were noticed in the center of the repair that did not connect to the edges of the repair. One was 31 in. long, and the other was 37 in. long. The west edge spall was 40 in. long and 1.5 in. wide. The east edge spall was 54 in. long, 1.5 in. wide, and 0.25 in. deep.	Low
		10,000	The center cracks did not extend. The west edge spall was 51 in. long, 2 in. wide, and 0.25 in. deep. The east edge spall was 63 in. long, 2 in. wide, and 0.5 in. deep. The east edge was producing up to 0.5-in. FOD. On the south edge of the repair a crack that was 18 in. long extending from the corner break was noticed. Another crack, which was 24 in. long, was in the center of the north edge. The repair had not failed; trafficking was discontinued.	Moderate

Table A4. Series 4 distresses noted during trafficking.

Repair	Description	Passes	Visual Observation	FOD Potential
12	6-in. cap/12-in. flowable fill base	0	Shrinkage cracks were noted mainly near the north edge and along the west and east edges.	Low
		112	More shrinkage cracks were noted, and some shrinkage cracks became longer. Some shrinkage cracks developed perpendicular from the east and west edges. The western joint started breaking up with many parallel cracks running together, particularly in the center of the joint. The eastern joint appeared the same as the western joint except in a slightly better condition.	Low
		560	No changes were noted.	Low
		1,008	The west edge spalling was 44 in. long and 1 in. wide with no FOD. The east edge spalling was 43 in. long, 1 in. wide, and 0.0625 in. deep. The FOD along the eastern joint spall was 0.125 in.	Low
		1,500	Not many changes were noted. The western joint cracks were the same, and approximately 75% of the edge had minor spalling with no FOD. The eastern joint had minor spalling from corner crack to corner crack with no FOD.	Low
		2,000	The center 8 in. was breaking up along the west edge. The spall was 0.25 in. deep and 0.5 in. wide with 0.25-in. FOD. The repair was also breaking up some along the south end of the western joint. The eastern edge cracks were connected to form a 41-in.-long and 1.5-in.-wide spall.	Moderate
		3,000	The center 24 in. of the west joint was breaking up with a maximum FOD size of 0.5 in. The spall was 1.25 in. wide and 0.25 in. deep. The center 4 in. of the east joint was starting to break up with a maximum FOD size of 0.25 in. The spall length was approximately 57 in. long, 2 in. wide, and 0.25 in. deep.	Moderate
		4,000	The west edge was broken up approximately 1 in. away from the joint. The max spall size was 60 in. long, 0.375 in. deep, and 1.25 in. wide. The maximum FOD size in the broken up spall was 0.25 in. The southwest corner had a spall breaking up from the crack. The eastern edge had a maximum spall size of 60 in. long, 2 in. wide, and 0.25 in. deep. The maximum FOD size was 0.75 in.	Moderate
		5,000	The west edge was broken up with small pieces of FOD (0.25 in.) from the center to the south end, and the entire length of the east edge was spalled with 0.25-in. FOD. The maximum FOD size was 0.25 in. The spall width and depths along the east and west joints did not change.	Moderate
		6,000	The entire west edge was spalled. The spall depth and width were 0.25 and 1.25 in., respectively. The east edge did not change.	Moderate
		7,000	No changes were noted.	Low
		8,000	No changes were noted.	Low
		9,000	No changes were noted.	Low
		10,000	The west joint was cracked along the entire edge with three broken up areas, each approximately 8 in. long. The maximum width was 1.25 in., and the maximum depth was 0.25 in. The east joint was cracked mainly along the center to the south end. The joints had minimal FOD.	Low
13	10-in.	0	Shrinkage cracks appeared mainly in the center of the repair and along the west edge.	Low

Repair	Description	Passes	Visual Observation	FOD Potential
	cap/12-in. flowable fill base	112	More shrinkage cracks developed, particularly along the edges and corners. Both the west and the east joints have a perpendicular shrinkage crack that developed (approximately 20 in. long).	Low
		560	Low-severity spalls were developing along the east, west, and south joints. Surface cracks were forming along the east, west, and north joints.	Low
		1,008	The east joint had a 14-in.-long by 1.5-in.-wide spall and a 21-in.-long by 2-in.-wide spall with no FOD or depth. The west joint had a 10-in.-long by 2-in.-wide spall near the south end of the joint with no FOD.	Low
		1,500	The west joint had parallel cracks along the edge, which began connecting. The east joint has a 68-in.-long crack. No FOD was noted.	Low
		2,000	The center area of the west joint began breaking up. The cracks were connected along the center and the south edge. The east joint was broken up in two areas. One area was approximately 22 in. long from the center to the south end, and the second area was approximately 30 in. long from the center to the north end. The maximum spall width along the east joint was 3 in. with 0.25-in. FOD.	Low
		3,000	The west edge was cracked along the entire edge; the spalled area was 48 in. long, 2.5 in. wide, and 0.125 in. deep with no FOD. The east edge had a maximum spall length of 65 in., width of 3 in., and depth of 0.25 in. with minimal 0.125-in. FOD.	Low
		4,000	The spalled area along the west edge was about 50 in. long, 2 in. wide, and 0.25 in. deep. The spalls along the east edge have opened up more with small FOD (0.25 in.). The spall size did not change.	Moderate
		5,000	The width of the spall on the west edge increased to 3.5 in. with minimal 0.25-in. FOD. The spall along the east edge expanded the entire length of the joint with a maximum FOD size of 0.25 in.	Moderate
		6,000	The west edge had cracking along the entire joint with no FOD. The east edge had no change.	Low
		7,000	The west joint had an open 7-in.-long spall in the center that was 2 in. wide and 0.25 in. deep with a minimal amount of 0.0625-in. FOD. The east joint had several spalls that had broken up with 0.5-in. FOD. The maximum spall length was 66 in., and the maximum width and depth were still 3 and 0.25 in., respectively.	Moderate
		8,000	No changes were noted.	Moderate
		9,000	The maximum spall width on the west joint increased to 5 in., and the maximum spall depth on the east joint increased to 0.375 in.	Low
		10,000	The west and east joints had minimal FOD. The cracks along the west joint were broken up. The maximum “open” spall was 15 in. long, and the maximum width and depth were 4 and 0.25 in., respectively. The spalls along the east joint were connecting and opening up. The maximum spall length, depth, and width were 68, 0.25, and 2.5 in., respectively.	Low
14	10-in. cap/12-in.	0	Shrinkage cracks were noted over a majority of the surface.	Low
		112	No changes were noted.	Low

Repair	Description	Passes	Visual Observation	FOD Potential
	flowable fill base	560	Cracks were noted in all four corners of the repair at the location of the intersection of the overcuts.	Low
		1,500	East and west edges had hairline cracks forming that were approximately 24 in. long.	Low
		2,000	The east edge crack increased to 43 in. in length, and the west edge crack extended the length of the repair.	Low
		3,000	The west edge crack began producing 0.25-in. FOD in the center of the crack over a 7-in. length.	Low
		4,000	Additional max 0.25-in. FOD was produced on the west edge crack.	Low
		5,000	Cracking was noted on the east edge of the repair where there was slight overfill. No new FOD.	Low
		6,000	No changes were noted.	Low
		7,000	The east edge cracking continued, producing a 2-in.-long spall and 0.25-in. FOD. Another 6-in.-long spall was noticed near the northeast corner, producing 0.25-in. FOD. The west edge produced two pieces of 1-in. FOD.	Low
		8,000	No changes were noted.	Low
		9,000	The east edge had a new 8-in.-long spall that was 2 in. wide with no FOD. No other changes were noted.	Low
		10,000	No changes were noted. The repair had not failed; trafficking was discontinued.	Low

Table A5. Series 5 distresses noted during trafficking.

Repair	Repair Description	Passes	Visual Observation	Overall FOD Potential
15	6-in. cap/12-in. limestone base	0	The repair had one 19-in.-long surface crack perpendicular to the center of the west joint, two 25-in.-long surface cracks perpendicular to the center of the south joint, one 26-in.-long surface crack perpendicular to the south end of the east joint, and two approximately 25 –in.-long surface cracks perpendicular to the center of the north joint. The southeast corner was also cracked.	Low
		560	The repair made popping noises when being trafficked. All four corners were cracked; the southeast corner appeared to be a corner break. The west joint was breaking up from the center to the south end; the spall was medium-severity. The east joint was breaking up near the north end. Parallel cracks developed at the center and south ends.	Low
		800	The spall on the south end of the west joint reached high severity. The maximum length was 60 in., width was 5.5 in., and depth was 1.75 in. The spall on the north end of the east joint reached high severity. The maximum length was 64 in., width was 4.5 in. and depth was 0.5 in. Both joints had a large amount of 1-in. FOD.	High
		1,008	The high-severity spall on the west joint further deteriorated. Lots of ¾-in.–FOD (max size of 1.5 in.) surrounded the spall. The total spall length was 73 in. long, and the high-severity spall was 36 in. long. The max width and depth were 5.75 and 1.75 in., respectively. The high-severity spall on the east joint also further deteriorated. The total spall length was 73 in. long, and the high-severity spall was 18 in. long. The max width and depth were 3.5 and ¼ in., respectively. Minimal ½ -in. FOD was around the high-severity spall.	High
		1,508	The repair made popping noises during the last set of passes. New surface cracks formed, and the existing ones spread in length. The east joint had a maximum spall width of 4 in. and a maximum depth of ¼ in. The west joint spall had a maximum length of 80 in., maximum width of 9.5 in., and maximum depth of 2 in. A large amount of ¾ - 1-in. FOD surrounded the east and west joints. The repair was considered failed.	High
16	8-in. cap/12-in. limestone base	0	The surface was rough with one 8-ft-long crack along the west edge and a corner crack in the southwest corner.	Low
		1,008	The east edge developed a 3.5-in.-long crack. The west edge developed a low-severity 12-in-long by 3-in.-wide spall.	Low
		2,000	The west edge spall increased to 39 in. long. The east edge crack increased to 49 in. long. The edges had minimal FOD.	Low
		3,000	The center 54 in. of the west edge was spalling and breaking up. The width was 5.5 in., and the depth was 1/8 in. There was a small amount of ¼-in. FOD. The center 65 in. of the east edge was spalling and breaking up. The width was 5 in., and the depth was ¼ in. There was a small amount of ¼-in. FOD with a maximum size of 1.5 in.	Moderate
		4,000	The west edge spall was 58 in. long, 4.5 in. wide, and 1/4 in. deep with minimal FOD. The east edge spall was 74 in. long, 5 in. wide, and 7/16 in. deep with a large amount of ¼-in. FOD.	Moderate
		5,000	The west joint did not change much. The spall was 80 in. long, 5 in. wide, and 9/16 in. deep. The east joint was much worse. The spall covered the entire length of the repair. The width was 9 in., and the depth was 1.375 in.	Moderate
		6,000	The spall along the west joint increased to 5.5 in. wide. The spall along the east joint increased to 1.5 in. deep.	Moderate
		7,000	No changes were noted along the west joint; however, a large amount of FOD was generated (0.25 to 1 in.), particularly along the east	High

Repair	Repair Description	Passes	Visual Observation	Overall FOD Potential
			joint. The spall depth along the east joint increased to 1.5 in.	
		8,000	The spall along the west joint did not change; the length was 80 in., the width was 5 in., and the depth was 0.56 in. The spall along the east joint covered the entire length of the repair and was 9 in. wide and 2 in. deep.	High
17	10-in. cap/12-in. flowable fill base	0	Each corner had a surface crack. The repair surface was rough.	Low
		1,008	The east joint had two 8-in.-long low-severity spalls that were each 2.5 in. wide. The west joint had one 6-in.-long low-severity spall that generated some 1/16-in. FOD.	Low
		2,000	The east joint spalls increased to 12 in. long, and the west joint spall increased to 30 in. long.	Low
		3,000	The center 58 in. of the west joint was spalling and breaking up. The width was 6.5 in., and the depth was 1/8 in. The ¼-in. FOD was minimal. The center 41 in. of the east joint was spalling and breaking up. The width was 3.5 in., and the depth was 1/8 in. The minimal FOD was also ¼ in.	Low
		4,000	The west edge had maximum spall dimensions of 72 in. long, 5.5 in. wide, and 7/16 in. deep with a large amount of ¼- to ½-in. FOD. The east edge had maximum spall dimensions of 42 in. long, 3.5 in. wide, and ¼ in. deep with some ¼-in. FOD in one area.	Moderate
		5,000	The west edge spall increased to 7 in. wide and 1.375 in. deep, and the east edge spall increased to 56 in. long and 1.25 in. deep. The east joint spall was broken up into large pieces.	High
		6,000	The west edge spall did not change in size; however, a large amount of ½-in. FOD (maximum size) was generated around the spall. The east edge spall increased to 4.25 in. wide. A large amount of FOD (maximum of 2 in. in size) was generated around the spall. Approximately 1/3 of the east edge was broken up.	High
		7,000	The entire west edge of the repair was spalled. The maximum width and depth were 7 and 1.625 in., respectively. The maximum spall dimensions along the east joint were 57 in. long, 4.25 in. wide, and 1.25 in. deep. Lots of FOD was around the west and east joints of the repair.	High
		8,000	The west joint increased in depth to 1.875 in. with a maximum FOD size of 1.5 in. The entire east edge of the repair was spalled with a maximum FOD size of ¾ in.	High
		8,500	The north and south edges were not distressed. The maximum dimensions of the spall on the west joint were 7.5 in. wide and 2.125 in. deep. The entire edge was spalled. The FOD ranged in size from 1/16 to 1.5 in. The entire length of the east joint was spalled. The maximum width and depth were 4.5 and 1.56 in., respectively. The FOD ranged in size from 1/16 to 0.75 in.	High

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14. ABSTRACT
During the period October 2013 through June 2015, research was conducted at the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, MS, to develop pavement design curves for airfield damage repairs (ADR) using Rapid Set Concrete Mix®. This report presents the technical evaluation of the field performance of full-depth concrete repairs conducted using Rapid Set Concrete Mix® over varying strength foundations and also presents the results of laboratory data collected during field testing. Passes-to-failure rates for each repair were determined using an F-15E load cart and were compared to those predicted using the Department of Defense's (DoD) rigid pavement design method. Results indicate that the DoD's rigid pavement design criteria are conservative at low pass levels with rapid-setting concrete and that the design guidance presented in this report should be used for ADR repair performance prediction purposes.

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